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DESCRIPTION AND CRITIQUE OF QUANTITATIVE METHODS FOR THE ALLOCATION OF EXPLORATORY DEVELOPMENT RESOURCES

C. L. Trozzo

May 1972

IDA
INSTITUTE FOR DEFENSE ANALYSES
SCIENCE AND TECHNOLOGY DIVISION

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13. ABSTRACT

This paper analyzes ten methods that have been used or proposed for planning the allocation of resources among projects within the Exploratory Development category of the Defense Research, Development, Test, and Evaluation Program. Each method is described in terms of a general framework of planning methods and of the factors that influence the allocation of development resources. A comparative analysis is made of the relative strengths and weaknesses of these methods.

The methods generally fall into two groups. Those in the more quantitative group try to express all important factors numerically, derive a single numerical measure of merit for proposed projects, and calculate precisely an optimum allocation of resources among the projects. Those methods in the less quantitative group do not try to measure numerically some important factors and leave the derivation of the allocation of resources among the various projects to the judgment of the responsible decision maker.

The more quantitative methods are uniformly more complex and difficult to apply. Such methods also generally fail to treat all of the important factors in the allocation problem accurately and adequately. For example, the risks involved in planning the technical, timing, and cost results of individual and groups of efforts are virtually ignored. Also, individual projects are treated as though they are quite independent of each other. Consequently, none of these methods can be recommended for use in their current form.

The less quantitative methods are primarily frameworks for recording and transmitting information that is important to the formulation of the development program. Because they do not attempt to devise a single optimum allocation of development resources, they are less likely to mislead program management than the more quantitative methods. Consequently, managers may find some one of these to be a convenient framework for organizing the information that they want readily available for deciding the allocation of development resources.

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ABSTRACT

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CONTENTS

ABBREVIATIONS

ACORD	Advanced concepts for ordnance
ADO	Advanced development objective
AFSC	Air Force Systems Command
AFRPL	Air Force Rocket Propulsion Laboratory
AMC	Army Materiel Command
BRAILLE	Balanced resource allocation information for logical lucid evaluation
CAL	Cornell Aeronautical Laboratory
CDC	Combat Development Command
CDOG	Combat development objectives guide
CDP	Contract definition phase
CL	Confidence level
DA	Department of the Army
DPQMDO	Draft proposed qualitative materiel development objective
DOL	Directorate of Laboratories (Air Force)
EDG	Exploratory development goal (Navy)
FDL	Flight Dynamics Laboratory (Air Force)
I.D.	Interdisciplinary (Team)
IR&D	Independent research and development
LAW	Light antitank weapon
MACRO R&D	Methodology for allocating corporate resources to objectives for R&D
MARS	Multiple artillery rocket system

NOL	Naval Ordnance Laboratory
NTF	Navy Technological Forecast
OCD	Operational capability objective
PQMDO	Proposed qualitative materiel development objective
PQMR	Proposed qualitative materiel requirement
QMDO	Qualitative materiel development objective (Army)
QMR	Qualitative materiel requirement
QUEST	Qualitative utility estimates for science and technology
SFC	Specific fuel consumption
SHORAD	Short-range air defense
SMEADO	Selected major exploratory and advanced development objectives
TORQUE	Technology or research quantitative utility evaluation
TPO	Technical planning objective
TRAADS	Technical Review, Army Air Defense Systems

I. INTRODUCTION, SUMMARY AND CONCLUSIONS

A. PURPOSE

The purpose of this Paper is to examine in detail the critical features of ten quantitative methods that may be used to allocate resources within the Exploratory Development category of the DoD Research, Development, Test, and Evaluation Program. It supports IDA Paper P-652, "Quantitative Methods for the Allocation of DoD Exploratory Development Resources" (Ref. 1). The ten quantitative methods examined are listed below:

1. Industrial Analog
2. TORQUE
3. Naval Ordnance Laboratory Method
4. Air Force Flight Dynamics Laboratory Method
5. Cornell Aeronautics Laboratory Method
6. Hercules Corporation Method
7. Army Missiles Plan
8. Air Force Directorate of Laboratories Plan
9. Army Research Plan
10. Another Service Method

No effort is made to review all the literature of the field in this paper; extensive bibliographies have been compiled by Baker and Pound (Ref. 2), and Cetron, Martino, and Roepke (Ref. 3).

B. PROCEDURE

To carry out the review, a general frame of reference is developed in the next chapter. This provides a convenient structure for comparing the various features of the quantitative methods. In

Chapter III, each method is described within this framework in order to make the similarities and differences of the various methods more evident. In Chapter IV, the methods are analyzed together according to each element of the general framework to highlight their relative strengths and weaknesses.

This analysis uses, in part, information that was developed from a number of visits to Government and industry laboratories and from interviews of professionals and managers engaged in this type of developmental work.

C. SUMMARY DESCRIPTION OF METHODS

Table 1 summarizes the structures and main features of the ten methods that are reviewed in this study. Each is described according to how it deals with such factors as value measures, operational requirements, technologies, costs, and risks.

D. CONCLUSIONS

The ten methods fall into two groups: a more quantitative group and a less quantitative group. The more quantitative methods (Industrial Analog, TORQUE, Naval Ordnance Laboratory, Flight Dynamics Laboratory, Cornell Aeronautical Laboratory, Hercules, and Another Service) structure the allocation problem and express its factors almost exclusively in mathematical terms. They generally devise a single numerical measure of merit for each proposed development project and use this measure of merit in formal calculations of the precise allocation of resources that should be made to each project.

The less quantitative methods (Army Missile Plan, Air Force Directorate of Laboratories Plan, and Army Research Plan) do not try to express mathematically some important factors in the allocation problem. They place much greater reliance upon managerial judgment to take such factors into account. These methods recommend an allocation of resources among proposed development efforts but without the numerical precision of the more quantitative methods and without contending that the recommendation is the single, most desirable allocation.

TABLE 1. SUMMARY DESCRIPTION OF METHODS FOR ALLOCATING DEVELOPMENT RESOURCES

	Structural Features and Factors Considered											
			Factors and Their Relationships									
	Primary Objective	Control Variables	Value Measures	Operational Requirements	Weapon Systems	Technologies	Development Tasks	Costs	Timing	Risk	Constraints	Decision Algorithm
Method	Devise an exploratory development program that:	Management's levers	Usefulness or contribution of program results	Major jobs of the Services	Instruments for performing jobs	Composition of systems	Work to achieve desired composition	Resources consumed in work	Time-phasing of resources and results	Probability of actual outcomes differing from expected	Limits on possible program options	Choosing pattern of development work to be done
1. Industrial Analog	Resembles the pattern of technological development in U.S. industry	Funds spent in major technical areas	None	Industry groupings--weapon categories	Individual weapons--industry products (DoD expenditures--industry sales)	Weapon-product lifetimes and technical complexity	None	DoD expenditures in 6.1, 6.2 and total RDT&E on technical field--company funded R&D in industry	None	None	None	Not specific--DoD funding proportional to industry in some way
2. TORQUE	Develops technologies having maximum "military value"	Funds to be spent in next year on project tasks	Subjective scaling of relative "military value"	Operational capability objectives (OCO's) assigned values	Alternative weapons for each OCO	Technological requirements of each weapon--criticality to system rated	Technical objectives sequenced in each technical requirement	Yearly and total funding for each project task	Weapon IOC--technical objectives--funding (timeliness function)	None	Total budget	ΔValue/ΔCost in descending order among project tasks
3. Naval Ordnance Laboratory	Develops technologies having maximum "value" for future Navy needs	Funds to be spent on each technology in next year	Subjective scaling of relative value for each factor	Warfare categories--targets--military functions assigned values	Contained in exploratory development goals (EDG) military worth	Technology pacing parameter linked to EDG by relevance measure	Implicit--different levels of pacing parameters	Aggregate expenditures on technology related to index of advance for parameter	Not explicit--progress possible in next budget year	None	Total budget	ΔPayoff/ΔCost equated over all technologies
4. A.F. Flight Dynamics Laboratory	Develops technologies having maximum "military value" for the Air Force	Funds and manpower to be devoted to each exploratory development task	Subjective scaling of relative effectiveness, timing, etc.	Operations within different types of wars--assigned values	Future A.F. flight vehicles from technological war plan--weighted for each operational requirement	Technologies linked to systems by applicability factor; separate technology goals	Confidence level gauge of achievement; contribution value links task to systems and technological goals	Funding for different levels of effort	Timing of technical objective, weighted by timeliness function	Probability that task output will fit system	Total funds, in-house and contract engineers	Linear program
5. Cornell Aeronautical Laboratory	Consists of tasks with maximum "expected value" to the Army	Tasks that will be performed	"Essentiality" of weapons developed	No general operational requirements. Background to qualitative materiel development objective (QMDO)	QMDO description of hardware. Weighting proposed	Combinations of technologies describe possible technical approaches to subsystems	Ordered tasks makeup technical approach resource pattern	Direct funds and other resources needed	Timing of QMDO's tasks	Probability of success for each task, technical approach, subsystem	QMDO requirements, funds, other resources	Decrease budget required by eliminating low Δ"Exp. Value"/ΔCost among technical approaches
6. Hercules Corporation	Contributes most to future company profits	Funds to be spent on individual development tasks	Profits generated by development work	Market characteristics	Projected systems using technology; contract research--sales, margins	Substitute and complementary technologies in each system	Technical goals of specific organized units of effort	Funding for each possible level of effort	Timeliness of marketing and time required for technical goals	Probability of predicted sales, margins, research needs, technical timing, and success	Total budget	Search possible shifts of funds among projects for mix giving maximum profits
7. Army Missile Plan	Supports preferred weapon concepts projected for future deployment	Weapons and funding of requisite tasks	Discrete priorities among weapons and technical work	Operational requirements in documents by CDC	Systems to fulfill operational requirements--priorities	Technical composition of system and subsystem concepts; general functional capabilities	Labs plan tasks for technical goals; tasks rated by contribution	Manpower, funding for planned tasks	Timing of funds, tasks, target dates of systems	None	None	Funds distributed down list of tasks ordered by priorities
8. A.F. Directorate of Laboratories Plan	Provides the technology required for probable future systems	Technical effort in each area	None	Desired capabilities defined by OSD and the Air Staff	System concept possibilities--most probable systems--subsystems	Technical planning objectives--technical gaps for systems; technical goals	Program elements--projects--tasks--technical efforts	Summary of resources for technical efforts--program elements	Desired capabilities set out in five year increments	None	None	None
9. Army Research Plan	Responds to long range concepts and objectives of the Army of the future	Funding emphasis for elements of program	Priorities	Future operational needs in 56 operational capability objectives	Not explicit--contained in long range technological forecast	Potential relevance of technologies in 30 6.2 elements to each OCO	237 projects in 6.2 elements; extra Army effort	Funding trends and planned support of elements--adequacy of support	Operational requirements out to 20 years; development program in next 1-5 years	Implicit--funding that gives reasonable probability of reaching technical goal on time	In-house capability, external efforts, directed work	Qualitative analysis of shifts in emphasis warranted from priorities, relevance, support
10. Another Service Method	Supplies technical advances for fulfilling overall Service mission	Funding of individual development projects	Subjective scaling of merit of requirements and contribution of technical objectives	29 operational requirements--merit weights	None	Technical objectives related to operational requirements	750 tasks--weights reflect contribution of each to each operational requirement	Estimated funding required to complete project	Projects set up to support operational requirements of 1982	Probability of success of each task to reach technical objective with funds, and in time	Sponsored projects, in-house capability	Rank projects by descending exp. value/cost

The conclusions are arranged according to whether they apply primarily to one of these groups or whether they apply to the methods in general.

1. <u>More Quantitative Methods</u>

Most of the more quantitative methods treat individual development efforts, weapon systems, and operational requirements as though their completion is independent of other efforts, systems, and requirements, respectively. This independence has not been demonstrated and probably does not hold in many significant cases.

The procedure used in these methods to impute military value to development efforts, weapon systems, and operational requirements requires that the efforts, systems, and requirements be independent of each other. To the extent that the independence does not hold, the values assigned to these factors may be highly inaccurate.

The linkage of the technological efforts to weapon systems and operational requirements is formulated in many of these methods in such a way that the technological efforts can determine the emphasis that will be placed on the development of various weapon systems and on the fulfillment of the various operational requirements. This reverses the procedural order by which the development program should be derived.

These methods are not specific about the scope of the resources that should be taken into account in the allocation problem. For example, they give no guidance on the treatment of such costs as the rents that should be imputed to the use of Government-owned real estate and the payments for resources that are financed from appropriations other than the Research, Development, Test, and Evaluation appropriation. The methods also do not propose how to treat the time distribution of funding requirements in the allocation problem.

These methods do not formulate adequately a framework for considering how actual technical, cost, and timing outcomes of a development program may jointly deviate from the point estimates made of these factors at the time the allocation decision is reached.

The workings of these methods are probably comprehensible to few of the participants in the allocation process outside the specialists who formulate the methods because of the complexity of (1) the formal decision algorithms and (2) the treatment given such factors as risk and the relationships among technologies in the composition of a weapon system.

2. Less Quantitative Methods

The less quantitative methods attempt primarily (1) to record information on some relevant considerations that must be made to determine the allocation of the development budget and (2) to transmit this information visibly to all levels of management.

These methods generally have more narrowly defined objectives than the more quantitative methods, focusing tightly on deriving a program of technological advances that would support a very specific set of projected weapon systems. Consequently, the chosen development projects should be both consistent with each other and with the development of some set of weapons.

Being tightly focused, these methods are not likely to consider a set of development efforts as broad as that brought to the surface in the more quantitative methods.

These methods rely heavily upon top management's judgment to consider, without guidance, factors such as (1) the technical, timing, and cost risks involved in a development effort and (2) the importance to a weapon system of a technological advance produced by a development effort. This leaves implicit much of the rationale for the final allocation so that it is difficult to review the rationale and to impose the allocation as an objective standard on other management and professional personnel for implementation.

These less quantitative methods may not choose the development projects best supporting higher order Defense goals because of the limited number of options they consider and the lack of precision in their treatment of important factors.

3. Both Groups of Methods

All of the method reviewed analyze the allocation of development resources that should be made in some future period. None analyze past resource allocations and project outcomes to develop a data base for applications of the method.

None of the methods measure the dispersion of estimates that might be made by a number of technologists and managers for projected factors such as costs, timing, technical advance, the importance of a technical advance, and the importance of a weapon system.

None of the methods make provision for tests of internal consistency. No tests appear to have been performed or proposed to show the differences in allocations that might result (1) from the application of the method by various decision groups to the same conditions or (2) from the application of the method by the same group to the same conditions at various times.

None of the methods have proposed a measure and procedure to test (1) how closely the resource allocation it proposes is actually implemented and (2) if its prescribed allocations are followed, how much better its development programs are relative to (a) programs prescribed by other methods or (b) programs devised without any formal allocation method.

E. RECOMMENDATIONS

Because of the shortcomings listed above, none of the more quantitative methods should be applied, in their current formulations, to determining the allocation of resources within Defense Exploratory Development.

Development of more quantitative methods for allocating resources within Exploratory Development should continue, however, because their rigorous structure should provide (1) a useful frame of reference for organizing information and regular liaison among systems specialists, technologists, and research managers and (2) a systematic procedure for searching out a development program that will best fulfill Defense goals.

- An investigation should be made of the delegation of goals by large, diversified companies to their research organizations for resemblances to the decentralized Defense Research and Development problem.
- More intensive study should be given to adapting to more quantitative methods the objective of funding technologies to support the set of future weapon systems that would maximize possible cost savings in performance of a fixed mission. The HINDSIGHT (Ref. 4) study of the cost savings generated by the C-141 and the AN/SPS-48 would provide a useful starting point for this work.
- Continuing study will be necessary to improve the quantitative expressions for (1) such important factors as cost, timing, technical advance, and weapon performance; (2) possible variances between predicted and actual values for these factors; and (3) the relationships of the technological components of a system and its performance.

While more quantitative methods are being developed, R&D managers should consider adopting the framework of a less quantitative method for organizing the information they should have readily available to determine the allocation of development resources.

If a less quantitative method such as those reviewed is adopted as an interim procedure, steps should be taken to incorporate into them more explicit and precise expressions for (1) the technical, timing, and cost risks in a development effort; (2) the relationship of a technical advance to a projected weapon system; and (3) the relationship of the various weapons to the fulfillment of the various operational requirements. Improvements must also be made in the cost concepts that should be used in the allocation procedure.

To demonstrate the reliability and benefits of any method for allocating development resources, further work on these methods should include the devising of measures for three kinds of tests:

- The dispersion of estimates by a number of technologists and managers of the expected values for important factors within the prospective development program such as timing, costs, technological advance, and operational requirement importance;

- The differences in the allocations that could result from (1) the application of the same method by a constant group of decision makers to the same conditions at different times, (2) the application of various methods by a constant group of decision makers to the same conditions, and (3) the application of the same method by various groups of decision makers to the same conditions;

- The extent to which the development program generated by a method is better than the program generated by any other method or by informal decision rules.

To facilitate the completion of such tests and the compilation of data that would be useful in the applications of the methods, further work should also include provision for continuous collection of information on actual resource expenditures, timing, technological advance, and applications of results of development efforts, in the same organizational units and formats as those used in the allocation method.

II. GENERAL MODEL

A. NEED FOR GENERAL MODEL

Initial study of the ten methods for allocating development resources gives a strong impression of diversity among them. Wide differences exist in their structure, in the general approaches they take to the allocation problem, and in the factors they take into account.

Review of these quantitative methods, therefore, requires a conceptually convenient, common framework of reference for organizing the basic features of the various methods. For present purposes, this framework is called a General Model. Such a General Model has at least two advantages: first, it helps resolve the differences in exposition among the various methods into parallel components; second, it lends a similar perspective to a review of the several methods.

In turn, use of the General Model helps to focus attention on a number of relevant questions about quantitative methods. For example: What does the method attempt to accomplish? Is that beneficial or useful? What factors does the method take into account? How does the method proceed to accomplish its objective? Are the procedural steps valid? Are the factors considered correctly? Is the resulting allocation consistent with the objective of the method?

B. STRUCTURE OF THE GENERAL MODEL.

There is no unique General Model into which the features of quantitative methods for allocating resources must or should be organized. A quantitative method may be broken down in different ways, depending upon the purpose of the analysis. The particular General Model that is reported below and illustrated in Fig. 1 has been useful for both general and technical analyses of the methods chosen for review in this paper.

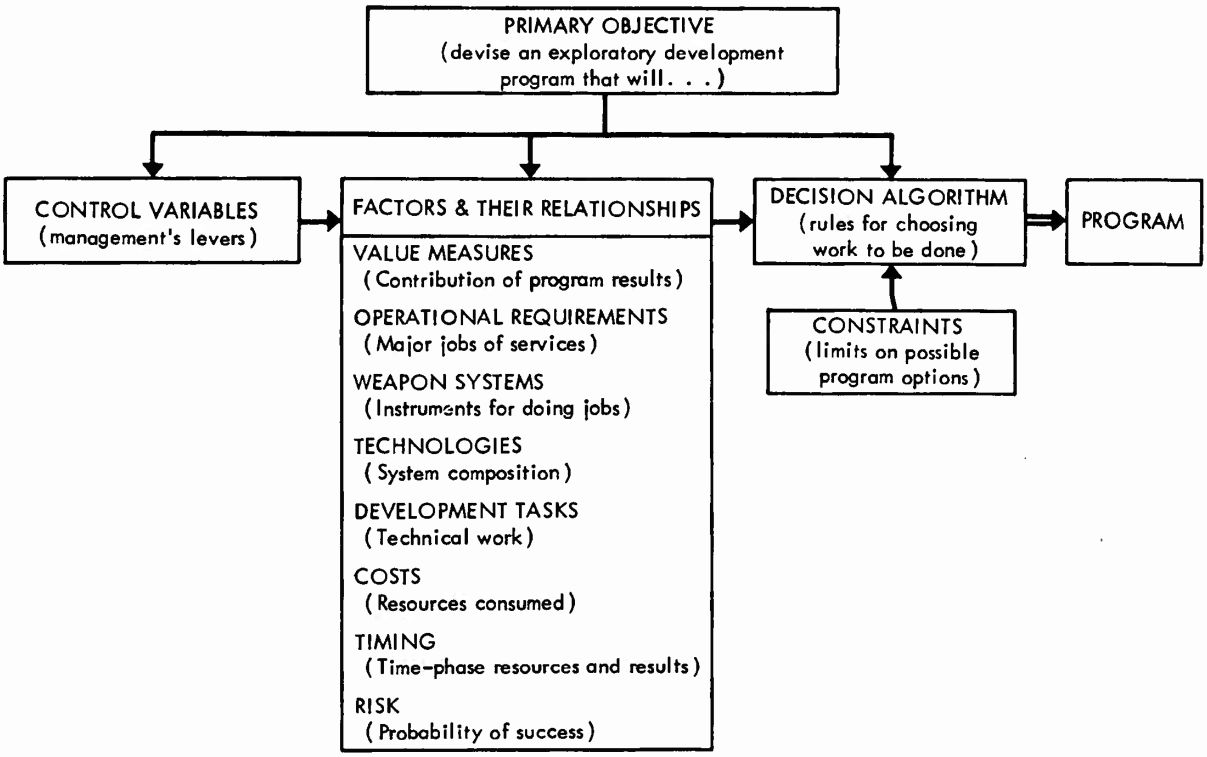


FIGURE 1. General Model

1. Primary Objective of the Method

All of the quantitative methods that were reviewed are directed at allocating development resources or choosing development programs; however, the different methods do frequently diverge in what they conceive the development program should accomplish. The purpose of the development program determined by the quantitative allocation method is treated in this paper as the primary objective of the method.

Development programs may have more than one objective, or hierarchies of primary and secondary objectives. Although the possibility of such hierarchies has been considered throughout the reviews, most cases can be resolved into a structure with a dominant objective, subject in some cases to secondary objectives.

2. Control Variables

Inasmuch as a quantitative method for allocating development resources is a tool for helping management at some level devise a development program, it must contain a concept of the factors over which management wants to exercise the power of decision. These factors are termed the control variables in the General Model. Management determines the magnitudes or go/no-go conditions for the control variables. Of course, other factors may be consciously affected by the choices made for the control variables but, for the purposes of examining the quantitative methods, this influence is regarded as an indirect one.

Distinguishing the control and other variables in a quantitative method is relatively important for review purposes because it must treat consistently what management controls, determines indirectly, and accepts as given.

3. Factors and Their Relationships

The factors incorporated into a quantitative method are the elements that the formulator of the method judges to have important effects upon the real development process and, therefore, should influence the allocation procedure of the method. Functional relationships among the factors are the formulator's mathematical or other representations of how factors influence one another, how control variables (a special class of factors) influence or are influenced by other factors, and how all the factors affect the measure of the primary objective of the development program.

Taken together, the factors and their relationships can be considered to be the quantitative method's characterization of the development process, describing the range of development work and allocations that are feasible within the terms of the method. The quality of the characterization directly affects the quality of the allocation that will be made by the method, inaccuracies in it possibly resulting in impossible or unbeneficial allocation schemes.

Specific factors that are taken into account can generally be combined according to the broader classes of features and activities in the development process that are described below.

a. <u>Value Measures</u>. Quantitative methods generally assign to the technological developments that are expected from a particular allocation of resources some overall measure of value for the agency undertaking the development program. These measures usually depict the extent to which the technological developments contribute to the achievement of the primary objective of the program.

The factors included within this class are those most directly related to the definition and determination of the value of the development program. For commercial enterprises, these factors would include features of the company's sales programs and markets that would determine the company's revenues or profits. Various value measures are frequently devised for Defense and other programs for which no market transactions occur.

b. <u>Operational Requirements</u>. The factors that are classified as operational requirements are those that specify the various missions that the Defense Department is charged with fulfilling and the general human and equipment capabilities that would contribute to those missions.

c. <u>Weapon Systems</u>. Weapon system factors are those that are related to the description of the operating and performance characteristics contained in the design of specific combinations of military equipment and personnel.

d. <u>Technologies</u>. For the purpose of the general model, technologies are the pools of skills and techniques that combine theoretical and practical information to devise processes and equipment for carrying out some operation. The related factors are those that set out the skills, techniques, and information that would be improved in the execution of the development program.

e. Development Tasks. The factors classified as part of the development tasks are those that are concerned with specifying the alternative combinations of manpower and equipment and the alternative approach strategies that might be employed to improve the skills, techniques, and information composing a technology.

f. Costs. Cost factors are those that specify and accumulate the real or implied payments that the development agency must make for the resources it employs in the implementation of its program.

g. Timing. Timing factors include those that determine the calendar time that will elapse with the progress of the development program. These factors are generally related to many of the factors already listed. However, to prevent much apparent repetition in the descriptions and analyses of the various quantitative methods, the methods of including timing considerations are reviewed together.

h. Risk. Risk factors are those that describe and take into account how the actual outcome of part of a development program may diverge in some aspect from what is expected at the outset of the program. As is the case with timing factors, risk factors are related to a number of the factors already listed above, but they may be treated as a group for expository purposes.

4. Constraints

In the organization of a quantitative method, constraints are the considerations, described literally or mathematically, that are basically external to the immediate development process of concern but must be taken into account in the formulation of the development program. Some considerations can be beyond the authority of the management of the development program but nonetheless crucial to its allocation of development resources. For example, the level of management at which the final allocation of resources is made among tasks may have some influence on the total budget it will receive, but by and large the budget is decided at a higher executive or legislative level. Consequently, that management must accept the funding available as a constraint on its program formulation.

5. Decision Algorithm

Within a quantitative method, the decision algorithm is the formal procedure that is applied to the allocation problem, as it is formulated in the components of the General Model described above, to choose the specific allocation that should be implemented.

III. DESCRIPTIONS OF QUANTITATIVE METHODS

In this chapter, each of the quantitative methods finally chosen for review in this study is described within the framework of the General Model developed in the previous chapter.

A. INDUSTRIAL ANALOG

Under contract to ARPA, Research Analysis Corporation performed work during 1969 to devise a quantitative method for planning resource allocation in the Defense Research and Exploratory Development Program categories (Refs. 5, 6). The proposed method, titled "The Industrial Analog," was not directed at the valuation or consideration of individual projects or specific tasks. Instead, it was aimed at aiding decision making at a more aggregative level, proposing to determine total expenditures on research and exploratory development by first determining the allocation of funds to a set of component scientific and engineering "technical categories." Statistical correlations were to be used in Industrial Analog to establish the funding of each "technical category."

1. Primary Objective of the Method

The principal objective of the Industrial Analog method is to determine the level of funding for the major technology fields within the DoD 6.1 and 6.2 program categories (Research and Exploratory Development) in such a way that the allocation of those development resources is similar to the pattern of expenditures made on basic and applied research by American industry.

The general guideline followed in the formulation of the method is that the Defense Department might well try in some way to imitate

American industry in determining the effort it should expend upon developing various technologies.

The rationale for DoD's imitating American industry rests mainly on the proposition that the commercial success generated by industry's R&D funding behavior might be translatable into national security success if DoD were to behave similarly.

> American industry as a whole has gained prominence in international markets for many of its products, and selected companies have gained and maintained competitive advantages over other members within their industrial group.... A selected industry-by-industry analysis of the proportion of company sales reinvested in basic and applied research was performed for the purpose of determining the existence of desirable analogs or guidelines for allocating the DoD resources (Ref. 6, p. 4).

2. <u>Control Variables</u>

In the Industrial Analog method, the principal variable controlled by the decision maker is the amount of funds to be allocated to a particular major scientific or engineering technical category. For these purposes, the 6.1 and 6.2 program work is grouped into nine such technical fields: (1) aircraft, (2) missiles, (3) combat vehicles, (4) combat vessels, (5) surveillance, intelligence and target acquisition, (6) data processing, (7) communications, (8) ordnance--nuclear and conventional, and (9) other.

3. <u>Factors and Their Relationships</u>

Because the Industrial Analog method is also concerned with the behavior of American industry in allocating development resources, all the factors it takes into account do not fit directly into the Defense terminology used in the general model. However, Defense counterparts exist for many of the concepts and measures that characterize American industry and these parallels are utilized for organizing the features of the method.

a. <u>Value Measures</u>. In the Industrial Analog method, no attempt was made to try to calculate the value that the respective Research and Exploratory Development efforts might have for the overall well-being of either industry or Defense.

b. Operational Requirements. As traditionally conceived, broad mission statements are not used for either industry or Defense in the Industrial Analog method but parallel concepts are used for classification purposes. For the Defense Department, weapon system or subsystem categories serve this function. These categories have already been listed under Section II-B-2 as the technical fields to which development funds are allocated.

Industry groupings used in the method can be considered as the commercial counterparts to Defense missions. The groupings selected for study were (Ref. 5, p. 5):

Chemical and allied products
Petroleum refining and extraction
Aircraft and missiles
Electrical equipment and communications
Motor vehicles and other transportation
Machinery
Professional and scientific instruments
Rubber products
Primary metals
Fabricated metal products

c. Weapon Systems. Specific weapon systems that had actually been deployed by the various Services and specific products that had been marketed by the companies in the industry groupings were listed and were to be taken into account in the analysis.

At the same time, the analysis was to incorporate consideration of total expenditures of DoD and the net sales of each industry grouping. These might be taken to be some measure of the quantity of the systems or products. However, it should be emphasized that total DoD expenditures and net industry sales have a broader scope and a different timeframe than the weapons and the commercial products of interest in the method.

d. Technologies. As defined in the general model, the specific technology content of the Defense weapon systems, commercial products, or the development programs of either Defense or industry is not described in the Industrial Analog method. However, somewhat relatedly, the method is concerned with the lifetimes of both military weapon systems and commercial products. In addition, the method proposes that the lifetimes of the systems and products should be related to their technical complexities through some functional representation. At the stage to which the study was carried, technical complexity was not defined.

e. Development Tasks. Being focused at a level somewhat above the planning of an individual project, the Industrial Analog method does not trace or specify the tasks that could be taken in the development programs of the various technical fields.

f. Costs. The costs taken into account in the Industrial Analog method are similarly aggregative.

For industry, the annual company-funded expenditures on R&D by each industry group are the principal measures of the R&D costs incurred. Using historical, time series data, the method proposed to relate the expenditures to annual net industry sales and these, in turn, to the corresponding commercial product complexities and lifetimes.

For DoD, expenditures on R&D at three levels are taken into account: first, DoD expenditures on each technical field in the 6.1 and 6.2 program categories; second, total DoD expenditures on the 6.1 and 6.2 program categories; and third, total DoD expenditures on RDT&E. A set of relationships of these measures was also proposed for analysis. Time series data covering annual DoD expenditures on each technical field in the 6.1 and 6.2 program categories were to be related, respectively, to corresponding total DoD expenditures, total DoD expenditures on the 6.1 and 6.2 program categories, and total DoD expenditures on RDT&E.

g. Timing. The Industrial Analog method does not attempt to explain, as such, the calendar time that has or must elapse in the pursuit of industrial and Defense development programs.

h. Risk. The Industrial Analog method does not treat explicitly for either industry or the DoD the possible divergence of the actual results of a development program from the results that were expected at the outset of the program.

4. Constraints

No limitations on the allocations to the different technical fields arising from considerations external to the development process have been included in the formulation of the Industrial Analog method.

5. Decision Algorithm

No formal decision algorithm has been devised for calculating the allocation of 6.1 and 6.2 funds to the different technical fields. Derivation of the procedure for determining the distribution of funds, using the statistical relationships described above and additional information such as DoD weapon system lifetimes and complexities, is listed as one part of the research that is still required to complete the project.

In the work reported, some evidence is given of the general criteria that are intended to be incorporated into the procedure.

> The objectives of the study are to (1) determine the proportion of sales invested by selected segments of U.S. industry in basic and applied research to maintain competitive products, and (2) derive criteria and a planning analog for making analytical comparisons between 6.1 (research) and 6.2 (exploratory development) defense expenditures and comparable U.S. industry expenditures. (Ref. 6, p. 5)

Among the remaining research required to develop the desired analog:

> Develop an industrial analog to defense research expenditures based on product competitive lifetime and complexity. (Ref. 6, p. 22)

B. TORQUE

In 1967 (Ref. 7), the Director of Defense Research and Engineering established an inter-Service ad hoc committee to investigate (1) methods for demonstrating the connections of current work in the Exploratory Development program category (6.2) to future Defense objectives and (2) approaches to attaining a balanced allocation of funds within the Exploratory Development program. In response to its charter, the committee formulated a quantitative technique to determine the distribution of the Exploratory Development budget. This technique is titled TORQUE, for Technology or Research Quantitative Utility Evaluation (Ref. 8).

In part because of common authors, TORQUE closely resembles a set of other quantitative analytical or allocation techniques including BRAILLE (Ref. 9), QUEST (Ref. 10), and MACRO R&D (Ref. 11).

In contrast to the aggregative allocations determined by a method such as the Industrial Analog, TORQUE focuses on determining the allocation of funds to individual project tasks. To do this, the formulation of the method includes several intricate relationships among a large number of factors that are used to characterize the weapon system development and utilization process. These relationships, in turn, are transformed into a set of mathematical expressions that are used in a formal computer program designed to optimize the allocation of funds.

TORQUE has been given quite serious consideration. Using the Air Force Flight Dynamics Laboratory as a test case in a simulated annual program development exercise, an attempt was made to assess the problems that might arise with its application to actual budget allocation questions.

1. Primary Objective of the Method

The primary objective of the TORQUE method is to choose the combination of development tasks and work units that maximizes the "military utility" derived from the weapon systems that result and the future military missions that will be served by these systems.

2. Control Variables

The principal control variables in TORQUE are the dollar expenditures that are to be made in the next year on project tasks or work units directed at a particular technology objective. In determining that allocation, a second-order control is established over the weapon systems that will be developed ultimately and the particular technical route of development that will be followed for each.

3. Factors and Their Relationships

The formulators of TORQUE have taken into account a large number of factors and introduced them into a rather extensive structure of relationships. These can be represented in a tabular form such as that shown in Table 2.

TABLE 2. TORQUE

OCO i	OCO Weight W_i	Systems ij	Systems IOC CY	Technical Objective, k=1			Technical Objective, k=2		
				Systems			Systems		
				A	B	D	B	C	D
x	100	A	'81-'82	C_{ijk}					
		B	'82-'83		0.3		1.0		
		C	'81-'83					0.5	
y	90	B	.		0.7				
		D	:			1.0			0.3
⋮		E ⋮							

$$u_k^F = \sum_i \sum_j W_{ij} C_{ijk} R_{Fk} t_{ijk}^F$$

$$R_{Fk} = \frac{F_{1k}}{\sum_y F_{yk}}$$

		A	B	k=2
Technical Objective Need Dates	Earliest	'76	'77	'76
	Latest	'77	'78	'77
Budget for Technical Objective (To meet latest need date)	CY 1971	F_{yjk}	F_{1B1}	
	1972	F_{2A1}	F_{2B1}	
	1973	F_{3A1}	F_{3B1}	
	1974			
TOTAL	⋮	___	___	

a. Value Measure. A special concept of "military utility" has been devised in the formulation of TORQUE to measure the value of different allocations of development resources. This concept is applied, with some variations, to the technological, financial, and time factors characterizing the different development projects and the missions and weapons to which the projects contribute. The component values are, in turn, transformed into a single measure to depict overall military usefulness.

In the derivation of the measure, each factor is evaluated in its special context by a group of experts that applies its collective judgment to assigning the factor a number that reflects quantitatively the criteria of the evaluation. The factors, the criteria of evaluation, the techniques of number assignment, and the integration of all these elements into the single measure of value are discussed in detail in the following sections.

b. Operational Requirements. One of the first inputs needed for the implementation of TORQUE is the definition of a set of Operational Capability Objectives (OCOs) by the top levels of management within each military Service, by the Joint Chiefs of Staff, or by the Office of the Secretary of Defense. Each OCO is a major mission that the Defense Department may be expected to carry out. It should be a rather broad or general operational function that the Defense Department would perform in support of U.S. national security goals over a long period of time, independent of any specific equipment that might be used to fulfill it. These missions are represented by the x, y titles in the column of Table 2 labeled "OCO."

Once the OCOs are defined, the same or similarly high-ranking officials must assign to each a numerical weight that corresponds to its relative importance among the Defense missions. These weights are the W_i's of the "utility function" illustrated in the column of Table 2 labeled "OCO Weight." They reflect the value schemes of the officials who must determine them in the light of their conceptions of the national security goals.

To ensure the internal consistency of the OCO weights, the TORQUE manuals describe and recommend application of the Churchman-Ackoff value measurement technique (Ref. 12, pp. 87-91). This technique was devised as a means of assigning approximate measures of value to various events. In order that the value of each event can be assigned by this technique the events must be independent. That is, the events can occur separately or in any combination, and if they do occur in a combination the value that would be attributed to the combination is the sum of the values assigned to each event as though it were to occur by itself.

c. Weapon Systems. In the TORQUE procedure, once the OCOs are defined, an inter-disciplinary team (I.D. team), composed of users, technologists, and systems analysts, devises alternative weapon systems or equipment-tactic concepts for carrying out the missions. As illustrated in Table 2, by System B, some of the systems may well be used in more than one mission. An example would be an aircraft that could be used in both strategic bombing and tactical interdiction.

The precise procedures that the I.D. team should follow are not spelled out in the manuals. The interaction of the personnel on the team determines the nature of its deliberations, the types of systems it will propose, the number of systems it will eventually incorporate into the TORQUE calculations for each OCO, and the criteria it will use to set the types and number.

d. Technologies. Using intelligence estimates and other information from long-range plans, the I.D. team makes a very rough design of each candidate weapon system serving the various OCOs. From these designs, the team further establishes the technology requirements of the systems. For example, the team may make a rough design of a long-haul airlift aircraft and then derive specific technology objectives for the propulsion system, the navigation system, and the landing gear, as well as for several other technologies, in fairly specific quantitative terms.

The team also must evaluate the "criticality" of each technology objective to the weapon systems. Definitions of the levels of "criticality" and the numerical values assigned to the factors representing these levels are given in Table 3. In Table 2, the "criticality" values are entered in the cell at the intersection of the system row in each OCO block with the column for the same system under the technology objective heading. For example, Technology Objective 1 has a "criticality" of 0.3 in Weapon System B when it is employed in OCO x but 0.7 when it is employed in OCO y. For a type of aircraft that might be used in strategic and tactical missions, Technology Objective 1 might be thought to apply to a component that affects low-altitude maneuverability. On the other hand, Technology Objective 2 might be related to the operation of an extremely accurate navigational system.

e. Development Tasks. A technology team composed of scientific and engineering personnel determines whether some of the technology objectives supporting the various weapon systems are sufficiently alike to be treated as a single technology objective (such as Technology Objective 1 in Table 2 being common to systems A, B, and D). This team also determines whether a group of technology objectives may fit into a single development sequence within which the accomplishment of some may be necessary for developing others.

f. Costs. Once the technology team has sorted out the technology objectives from the various weapon systems, it proceeds to estimate the time-phased funding that will be required for the development of each objective. The timing features that are considered in these estimates are described more fully in the following paragraphs.

g. Timing. Given the development of the threat, current system capabilities and current procurement and phase-out plans, the I.D. team must estimate the earliest date by which a new system might be introduced into the force and the latest date by which it could be

TABLE 3. CRITICALITY OF A TECHNOLOGY OBJECTIVE TO A WEAPON-SYSTEM/OCO COMBINATION

(The assumption is that the objective of the technical effort will be accomplished.)

Absolutely Essential

Failure to have this technology will absolutely prevent the attainment of the capability desired........................1.0

Major Contribution

Failure to acquire this technology will result in a significant decrease in one or more of the major performance parameters needed to attain the capability desired. Such degradation probably would not prevent a favorable decision for development of equipment for the inventory..0.7

Cost Reduction

Success in achieving this technology will provide a major reduction in the cost of achieving the capability desired...0.5

Substantial Contribution

Failure to achieve this technology will result in the loss of a highly desirable but not essential capability. Such degradation, while important, probably would not prevent a favorable decision on the development of equipment for the inventory to attain the capability desired..........0.4

Refinement of Capability

Achievement of this technology will result in some refinement of the present capability. The desired capability, however, could be achieved without this effort..0.3

Indirect Contributions

Achievement of this technology will only be an indirect contribution to the capability desired...........................0.2

Remote Association

This effort has only a remote association with the capability desired...0.1

No Contribution...0.0

Source: Ref. 8.

introduced without loss of effectiveness. For the illustrations in Table 2, the initial operating capability dates, in calendar years, are listed in the column titled "Systems IOC CY."

Consideration of the system IOC dates must feed back onto the I.D. team choice of systems to be proposed. There would be little point in proposing an "obsolete" system or a system that could not be introduced before the effectiveness of the preceding system in the force deteriorated significantly.

Subsequently, the I.D. team must estimate the dates by which attainment of the technology objective is needed to support the system IOC dates. The need dates depend upon the lag between the date the technology is demonstrated in Exploratory Development and the date it can finally be incorporated into actual production for procurement in a new weapon system. In Table 2, Technology Objective 1 must be demonstrated by 1976 at the earliest and 1977 at the latest to permit Weapon System A IOC dates of 1981 or 1982.

In line with the I.D. team determinations, the technology team estimates a time-phased budget for each weapon system application of a technology objective, the pattern of annual funding set so that the completion of the technology objective will match the latest need date for that application. These are illustrated in Table 2 by the entries F_{yjk} in the last rows of the table. For example, F_{2B1} is the funding of Technology Objective 1 that will be required in the second year to develop the technology objective in time to meet the 1978 need date for Weapon System B.

In TORQUE the assumption is made that a technology objective is not worth its full "utility" in a particular weapon system application if it is completed outside the interval of its earliest and latest need dates for that application. This assumption reflects two considerations. If the technology objective is developed before the early need date, the resources used in its development might have been better used in some other effort. If the technology objective is developed after the late need date, the effectiveness of the system it supports will have deteriorated. The analytical form of the assumption used in TORQUE is the Timeliness Function, t^F_{ijk}, illustrated in Fig. 2.

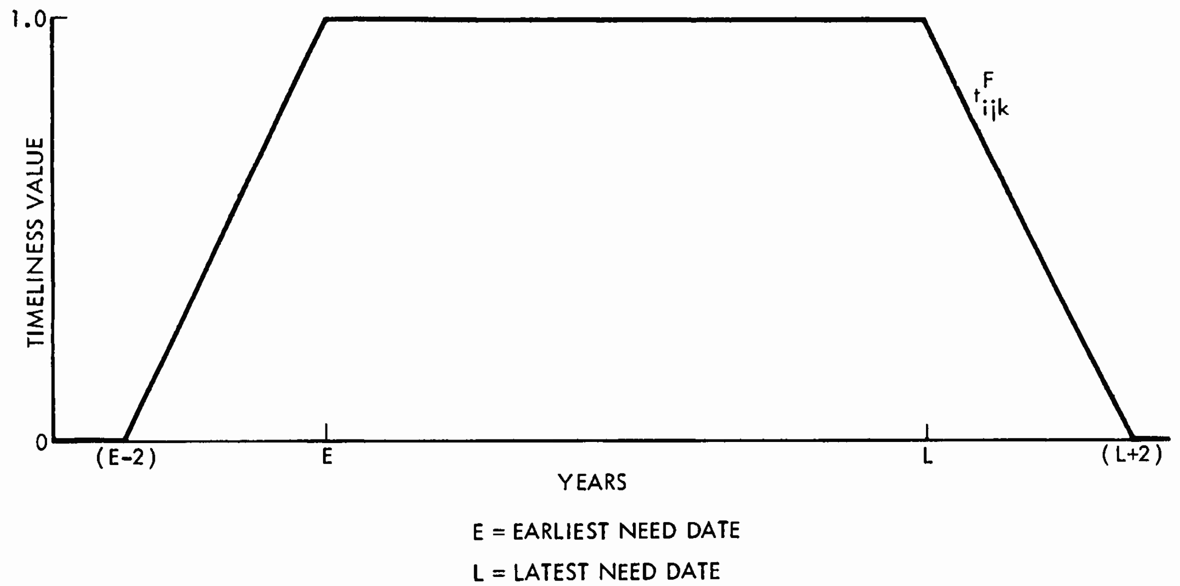


FIGURE 2. TORQUE Timeliness Function

The value of t^F_{ijk} depends basically upon the funding devoted to the technology objective in the next year, F_{lk}. For any F_{lk}, an estimate is made of the completion date of the resulting development program for the technology objective. In general, if F_{lk} is less than the first year funding in the time-phased budget originally estimated by the technology team for the particular application, F_{ijk}, the completion date will be set back from target date used by the team. If F_{lk} is greater than the first year funding in the team's original budget, F_{ijk}, the completion date will be moved forward from the target. The completion date, in turn, is compared with the technology objective need dates specified for the particular weapon system and the value of t^F_{ijk} is then set according to the trapezoid-shaped relationship shown in Fig. 2.

h. Risk. The formulation of TORQUE does not take into account that the actual progress in technical performance, timing, or cost of a development effort contributing to a technology objective may deviate from the projections made of these variables at the time the allocation of resources is made. The development process is treated, more or less, as precisely predictable.

4. Constraints

In TORQUE the total budget made available to the program is the principal consideration external to technology development that is imposed upon the choice procedure. However, as explained in the experimental test manuals (Ref. 8), the set of candidate weapon systems incorporated into the TORQUE choice framework is specified beforehand, apparently on the basis of considerations outside those taken directly into account in TORQUE. Consequently, the choice of systems made by TORQUE in allocating resources to the Exploratory Development program is also constrained.

5. Decision Algorithm

All of the factors and relationships that have been described are components of the terms in the "utility function."

$$U = \sum_k u_k^F = \sum_k \left(\sum_j \sum_i W_i C_{ijk} R_{Fk} t_{ijk}^F \right)$$

where U = total "military utility," or overall "utility function"

u_k^F = "utility" of work on technology objective k when funded at level F_{1k} next year, the technology objective "utility function"

W_i = relative weight of operational capability objective i, the basic measure of value

C_{ijk} = the "criticality" of technology objective k for weapon system j when employed in operational capability objective i

$$R_{Fk} = \frac{F_{1k}}{\sum_y F_{yk}}$$

F_{1k} = dollar funding of work in technology objective k next year, the <u>control variable</u>

F_{yk} = dollar funding of work in technology objective k in year y

and t^F_{ijk} = the timeliness function value for technology objective k in system j applied to operational capability objective i when funded at F_{1k} next year.

As defined above, the utility function is composed of the separate utility functions of the individual technology objectives. However, each of these technology objective utility functions is further decomposable into more basic utility functions defined by the relationship of the technology objective to a specific weapon system with the funding, F_{1k}, variable. In each of these more basic utility functions, W_i and C_{ijk} are constants; R_{Fk} and t^F_{ijk} vary with F_{1k}. R_{Fk} varies from 0 to 1 as F_{1k} varies from 0 to $\sum_y F_{yk}$. However, t^F_{ijk} varies from 0 to 1 and back to 0 as F_{1k} increases.

Consequently, the basic utility functions, technology objective utility functions, and the general "utility function" can be made dependent, in the first instance, upon the quantity of funds spent in the relevant part of the development program. A basic utility function will generally have a single peak or maximum but the technology objective utility function, formed by aggregating basic utility functions, may assume quite irregular shapes.

Besides being a component of the utility function the cost relationship, which depicts the funding requirements of the progress on a technology objective, is used separately in the choice procedure and the budget tabulations of the algorithm.

A very specific algorithm has been devised in TORQUE to determine the distribution of the program budget among the candidate technology objective tasks and work units. Basically, the algorithm tries to take into account simultaneously the contributions of the technology objectives to the utility function, the costs of the technology objective contribution to the utility function, and the overall program budget constraint.

To some extent, the algorithm resembles a Lagrangian multiplier maximization technique in the solution to which the incremental contribution of utility would be approximately the same from the expenditure of the last dollar in each technology objective. In other words, it attempts to allocate total available funds among the technology objectives in such a way that any reallocation of funds among the technology objectives would not increase the value of the utility function. The algorithm performs the allocation in a sequential fashion (described in the Appendix) assigning additional units of funds to the various technology objectives in the order of descending increments of utility per additional dollar expenditures within and across all technology objectives.

6. Special Aspects

Following from the nature of the control variables and the criteria considered in TORQUE, the resulting solution displays the total funds that should be spent on each Exploratory Development project task or work unit during the next program year. According to the TORQUE manual, that solution could then be used in the followup exercise, stepping up by one year the budget proposals of the technology team, to determine similarly the "optimum" allocation of funds in the subsequent year. This procedure can be extended farther into the future to generate a time-phased distribution of funds for Exploratory Development, tracing out the later program impacts of the current and near-term funding decisions.

C. NAVAL ORDNANCE LABORATORY METHOD

In 1968, under a task from the Exploratory Development Division of the Naval Material Command, the Naval Ordnance Laboratory undertook to devise a method for planning the distribution of Exploratory Development resources among the various technologies. The NOL study built upon work already performed on the Navy Exploratory Development Goals (EDGs) and the Navy Technological Forecast (NTF) to formulate a quantitative system for planning the Exploratory Development program (Ref. 13).

Like TORQUE, the NOL method is made up of relationships among a number of factors, including military missions, weapon system configurations, technology efforts, and costs. These relationships are formulated into a mathematical model to which a formal decision algorithm is applied to determine the desired allocation of development resources among the various technologies.

1. Primary Objective of the Method

The primary objective of the NOL method is to allocate the development budget among the various technologies to produce the Exploratory Development program having the maximum value for future needs of the Navy. Value and the future needs of the Navy have specific meanings for the purposes of the method. These meanings are described in some detail below.

2. Control Variables

In the NOL method, the principal control variable of the manager is the quantity of funds that will be devoted to work in a particular technology during the next budget year. As in TORQUE, however, the funding exercises much broader second-order control over the types of weapon systems that will be ultimately developed and the particular missions that will be emphasized.

3. Factors and their Relationships

The NOL method considers a number of factors in devising its allocation of development resources among the technologies. These factors are incorporated into relationships that the formulators have devised to describe the interactions of the factors and, ultimately, their effects in the real development process.

a. Value Measure. "Value" is attributed to each technology competing for funds in the method. However, the value of any technology is derived from the values attached to a set of factors that is treated as more basic for development planning. For these purposes, value is measured on an arbitrary scale, using a number system to depict the relative rankings of the technologies and more basic factors. The derivations are described more fully below under the various factors that are taken into account and the overall synthesis of the factors for determining the budget allocation.

b. Operational Requirements. A special hierarchy of missions and functions is used in the NOL method to define its counterpart concept to operational requirements. The three-level classification scheme has the following structure:

A. Warfare Categories
   1. Strategic
   2. Conventional
   3. Limited and Counterinsurgency

B. Target/Support Categories
   1. Air Target
   2. Sea and Land Surface Target
   3. Undersea Target
   4. Information Support
   5. Logistics and Ancillary Support

C. Military Function Categories
   1. Command and Control
   2. Target Data Collection
   3. Counteraction
   4. Mobility
   5. Support

An operational requirement is described in terms of a combination of elements taken from these categories. For example, one might be a close-support capability (military function) against sea and land surface targets (target/support) in a conventional war (warfare).

Values of these operational requirements are synthesized from weights assigned to each of the elements within the three categories. These weights are determined through a polling procedure much like that recommended in TORQUE, and also employing the concept of an approximate measure of "utility" proposed by Churchman and Ackoff (Ref. 12).

The value of an operational requirement can be represented in the following fashion:

$$w_{abc} = w_a w_{b:a} w_{c:ab}$$

where w_{abc} = the value of an operational requirement composed of military function c, target/support b, warfare a

w_a = the weight assigned to warfare category a, based on its importance in supporting basic national objectives in the time period under consideration

$w_{b:a}$ = the weight assigned to target/support category b, based on its contribution to the objectives of warfare type a

$w_{c:ab}$ = the weight assigned to military function c, based on its importance to target/support category b in warfare type a.

c. Weapon Systems. Descriptions of weapon system capabilities are contained in the Exploratory Development Goals (EDGs) employed in the NOL method. Specifically, the EDGs describe the work that must be done at the Exploratory Development level to satisfy the operational requirements of future weapons and support systems. They translate the broad and intentionally general statements made in long-range planning documents into specific, quantitative terms that will facilitate planning of Exploratory Development programs responsive to Navy needs. For example, the EDG for a surface close-support capability to be employed against sea and land surface targets will describe with some precision several quantitative performance measures, including the required CEP, the delivery range, and damage criteria. (Ref. 13, p. 2-2).

In turn, the EDG is assigned a weight in a manner similar to that already described for the operational requirements above, based upon its "importance" (relative to other EDGs) to the military function it serves. If this weight for EDG j is designated $w_{j:abc}$, the "military worth" (value) of EDG j can be represented in the following way.

$$W_j = w_{j:abc}w_{abc} = \text{the "military worth" of EDG } j$$

d. Technologies. Basic technologies are spelled out in some detail in the NOL method. The areas of technology devised for the Navy Technological Forecast have been adopted for these purposes. Each technology is depicted in terms of a "pacing parameter." A pacing parameter is generally a measure that has been devised to communicate readily an operational feature of a technology. For example, within rocket propulsion technology, the specific impulse of a rocket propellant measures the impulse that can be theoretically generated from the reaction of that specific combination of a fuel and oxidizer. It is stated in terms of the number of seconds over which one pound of the propellant will generate one pound of thrust.

Technologies are linked to the EDGs in two steps. First, a general functional analysis is made of each weapon system described in the EDGs. Second, expert judgment is applied to devising the technological content of each general functional area, in terms of the areas of technology contained in the Navy Technological Forecast.

Once the linkages between the technologies and EDGs are established, the expert judgment is used again to establish the "utility" of each technology to each EDG. In this case, utility is intended to be a measure of the relevance of the effort required to advance the technology to satisfy the EDG. The expert (1) "predicts" whether the state of the technology (the pacing parameter) will be adequate to meet the functional requirements, (2) assigns numerical values to describe the conditions of adequacy, and (3) "normalizes" these values for each EDG to show the relative importance of work in each technology for the EDG.

The numerical values that describe the adequacy of a technology's pacing parameter to the functional requirement of an EDG are called "relevance numbers." These are denoted by r_{ij}, the adequacy of technology i for the functional requirements of EDG j.

r_{ij} = 4, if the forecast state of technology i is less than required for EDG j,

= 2, if the forecast state of technology i equals that required for EDG j,

= 1, if the forecast state of technology i exceeds that required for EDG j,

= 0, if technology i is not related to EDG j.

Finally, the "utility" of technology i to EDG j is derived by normalizing the relevance numbers of the various technologies that apply to that EDG.

$$u_{ij} = \frac{r_{ij}}{\sum_i r_{ij}} = \text{the utility of technology i to EDG j.}$$

e. Development Tasks. The NOL method does not explicitly deal with the different combinations of manpower and equipment or the different approaches that might be used to advance the pacing parameter of a technology. However, it does contain a rudimentary concept of the development task insofar as it admits that the pacing parameter can be pushed to different levels, depending upon the effort expended on the pacing parameter.

f. Costs. Cost components and cost estimating techniques are not treated in detail in the formulation of the NOL method. The general approach adopted relates the funding of a technology to the progress that would be made in the pacing parameter of that technology over the funded time period, without regard to the actual resources employed.

To describe this relationship, an "Index of Advance" has been devised for each technology. Basically, this index measures the progress that would be made in the pacing parameter of the technology under different funding levels during the next budget year relative to the theoretical maximum progress that would be made if unlimited funds were available.

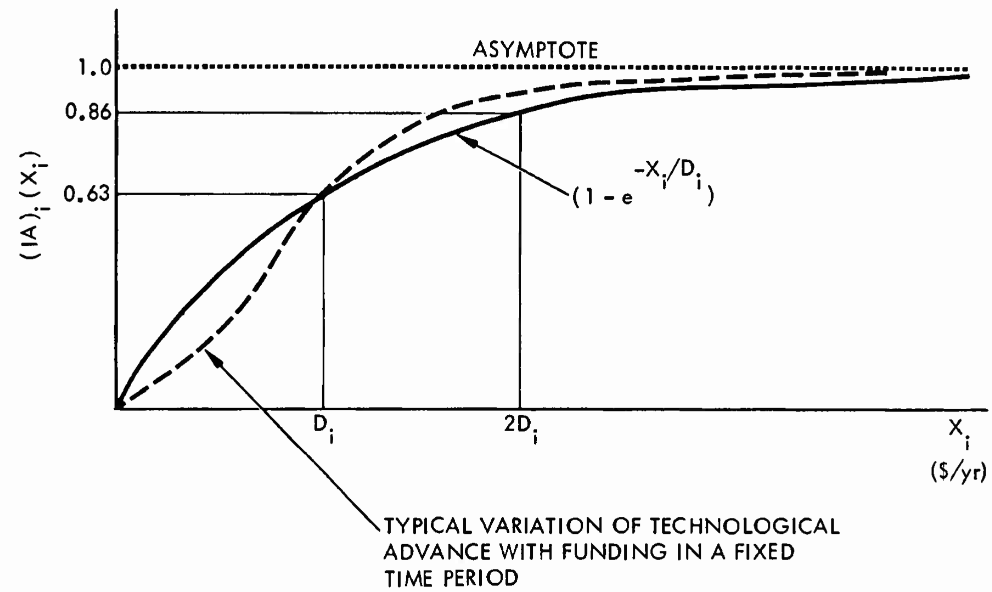
$$(IA)_i(X_i) = \frac{\text{Advance in parameter i during plan time with funding } X_i}{\text{Advance in parameter i during plan time with no fund limit}}$$

An exponential approximation to this empirical relationship is used in the NOL method.

$$(IA)_i(X_i) = 1 - e^{-X_i/D_i}$$

An illustration of an index of advance is shown in Fig. 3 along with the exponential approximation. To follow the example cited above, the index might be taken to show the specific impulses that might be developed in new propellants resulting from different levels of expenditures on Exploratory Development in this technology relative to the specific impulse that might be attained with unlimited expenditures in the technology.

g. Timing. The timing of the EDGs and the development efforts that must be performed for their fulfillment are not treated explicitly in the NOL method. Consideration of calendar and elapsed time must be assumed to be made with the specification of the EDGs, their functional analyses, and technological links. The most direct reference to time is contained in the index of advance, which measures the progress that will be made in a particular pacing parameter within the following budget year as a result of the funding that will be devoted to that parameter during the same time.



X_i = Dollar expenditure on technology i in next year

D_i = The dollar expenditure on technology i in the next year that would result in the pacing parameter progressing to a level 63% of the total progress possible with unlimited funding.

FIGURE 3. Simulation of a Typical Index of Advance Curve Using an Exponential Function

h. Risk. No explicit consideration is given to the possible deviations that might occur between the projected quantities and actual outcomes of the pacing parameters, costs and time requirements of the development effort depicted in the NOL method.

4. Constraints

The principal constraint considered in the formulation of the NOL method is the maximum total budget that will be available to be spent on the relevant development effort over the next funding year.

5. Decision Algorithm

The components of the analysis in the NOL method, described above, are integrated into a "Payoff Function" that measures the value of any distribution of funds among the technologies, subject to a budget constraint.

$$P(X) = \sum_i (IW)_i (IA)_i (X_i)$$

$$\sum_i X_i \leq C$$

where $P(X)$ = the total Payoff or "Value,"

$(IW)_i$ = the "Index of Worth" of technology i,

$= \sum_j W_j u_{ij}$

W_j = the "Military Worth" of EDG j,

u_{ij} = the "Utility" of technology i to EDG j.

$(IA)_i(X_i)$ = the "Index of Advance" of technology i, a function of X_i,

X_i = the amount of funds allocated to Exploratory Development in technology i, during the next planning year,

C = the total budget available for Exploratory Development during the next planning year.

To determine the allocation of funds among the various technologies that has the maximum value for Navy needs, the NOL method applies an algorithm resembling a Lagrangian multiplier maximization technique to the payoff function and budget constraint. Consequently, the distribution of funds is determined in a way that the last dollar increment allotted to a technology in the Exploratory Development program generates the same increment in the payoff function as the last dollar increment alloted to any other technology.

D. AIR FORCE FLIGHT DYNAMICS LABORATORY METHOD

Beginning in 1962, the planning staff at the Air Force Flight Dynamics Laboratory (FDL) developed a quantitative method to assist in allocating the Lab's Exploratory Development budget among the proposed tasks. In its formulation, the staff has incorporated a number of factors and analytical features to establish the value of the various tasks. The approach imputes these values both through the weapons systems that the tasks might eventually support and through a set of more basic technical goals that are not directly associated with projected weapons systems.

Originally, the value estimates were incorporated into a linear programming model through which the desired allocation of the budget among the tasks was derived. According to reports on the method, experimental solutions were obtained shortly after the formulation work began and, with additional development, solutions have been derived for a wide range of management problems. (Refs. 14, 15)

Interestingly enough, the Air Force Flight Dynamics Laboratory was the site of the principal trial that has been run on the TORQUE allocation method.

1. Primary Objective of the Method

The primary objective of the FDL method is to choose the levels of effort that should be expended upon the different proposed Exploratory Development tasks to produce the maximum military value to the Air Force. The definition of military value and its measurement for each task are treated in detail below.

2. Control Variables

The principal control variables in the FDL method are the various amounts of resources, dollars, and types of engineering manpower that are to be devoted to each Exploratory Development task. These resources are treated in packages of discrete quantities that can be applied to each task, but linear combinations of these discrete quantities are also admissible.

3. Factors and Their Relationships

a. Value Measure. Like TORQUE and the NOL method, the FDL method employs the Churchman-Ackoff approximate measure of value as its basic value concept (Ref. 12). In this particular application, the measure is used as a quantitative expression of the "effectiveness" of the various development tasks. Rankings of technological, timing, and mission factors, based on various criteria, are transformed through a judgmental process into numbers that depict, on a continuous scale, the value of the tasks to the Air Force in its role supporting national objectives.

b. Operational Requirements. The formulators of the FDL method used the following scheme of wars and operations to define the pertinent operational requirements of the Air Force.

Wars

- General
- Limited
- Cold

Operations

- Combat
- Reconnaissance
- Logistics
- Show of Force

A particular operation in the context of a single type of war is treated as a separate mission or operational requirement.

The Churchman-Ackoff procedure is employed to establish the value of an operational requirement for the purposes of Exploratory Development. The number associated with operation type j in war type i, w_{ij}, indicates the relative technological improvement that is needed to support that type of operation in the specific war context.

c. Weapon Systems. The range of weapon systems considered in the FDL method consists of the future conceptual Air Force flight vehicle systems proposed in the Air Force Systems Command Long-Range Technological War Plan. A value is assigned to each weapon system corresponding to the support it should provide each mission relative to the other weapon systems. These values, R_{ij}^{m}, reflecting the relative contribution of system m to the ij mission, are derived by the same Churchman-Ackoff approximate value procedure. In turn, the system mission values are combined to form an overall system value.

$$S_m = \sum_{ij}\sum w_{ij} R_{ij}^{m} = \text{the raw value of system m}$$

where w_{ij} equals the mission values described above.

Finally, the system values are normalized so that

$$\sum_m S_m = 1.$$

d. Technologies. The technological composition of each weapon system is specified and connected to the technological accomplishments that are sought in the specific Exploratory Development tasks proposed for the FDL program. The connection is quantified in the applicability factor, D_{nm}, which ranges from 0.1 to 1.0 depicting the applicability of the technology in task n to weapon system m.

However, in addition to the weapon-systems-oriented path to the valuation of a development task described above, the FDL method includes a technology-oriented valuation scheme as well. Technical goals, defined in the Research and Technology Long-Range Plan, are related directly to the various missions without reference to any weapon systems in which they eventually might be embodied. A technical goal, k, is assigned a value G_{ij}^{k}, reflecting its contribution to fulfillment of the ij mission relative to the contributions of other technical goals to that mission. These values are combined to devise an overall value for the technical goal.

$$\sum_{ij}\sum w_{ij} G_{ij}^{k} = T_k = \text{the overall value of technical goal k,}$$

where w_{ij} is the mission values described above.

e. Development Task. The development task is the basic work unit that is used in the FDL method for programming the Exploratory Development effort of the Laboratory. Each task is characterized primarily in terms of the particular aspect of technology to whose development it is directed. The final product at which it is aimed is a fairly well-defined technology objective.

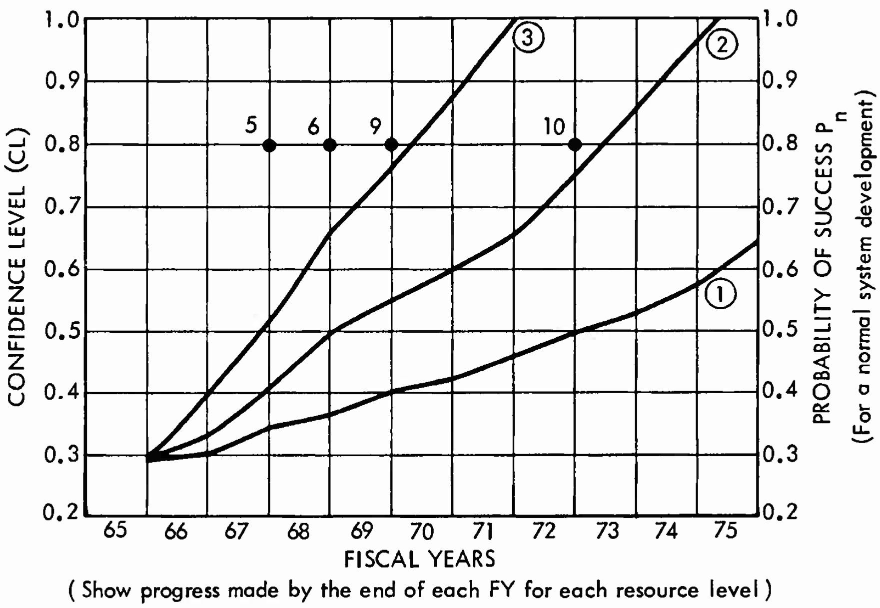
Progress of a task is measured by the responsible task engineer's assignment of a value to a descriptive variable designated the confidence level. For a particular development task, n, the confidence level, $(CL)_n$, may assume a value ranging from 0.1 to 1.0 in 10 discrete units. In this range, the value 1.0 indicates the fulfillment of the task's technology objective.

From another viewpoint, the individual development task is also described in terms of the funding rates and the amounts of in-house and contract engineers that should be devoted to it to achieve different levels of $(CL)_n$ within different time frames.

Each development task is related specifically to each proposed weapon system and each technical goal. This relationship is depicted in a task contribution variable. For task n, b_{nm} is assigned a value ranging from 0.0 to 1.0 to indicate its contribution to system m. The lower end of the scale signifies that the task is only remotely associated with the weapon system; the higher end of the scale signifies that it is absolutely essential to completion of the weapon system.

Another variable, b_{nk}, indicates that contribution of task n to technical goal k. The range of b_{nk} extends from 0.0 to 1.0 with lower values signifying that the task would make only a minor contribution to technical goal k and the higher values signifying that the task might contribute a potential breakthrough to the fulfillment of the goal.

f. Costs. As indicated in the above description of the development tasks, the costs tallied for each task are the funding rates that are required for both the in-house and contract work that would be undertaken at different levels of effort. In turn, each level of effort and the costs that it entails are related to the changes that their implementation would bring about in the confidence level of the task (the extent to which the technology objective of the task is fulfilled) in different time frames. These relationships are displayed in Fig. 4. In carrying out the analysis, three funding rates are considered: (1) one-half the currently scheduled funding, (2) the currently scheduled funding, and (3) double the currently scheduled funding. These three levels are illustrated in the hypothetical case shown in the figure.



(CL) Measures progress toward fulfillment of Task technology objective

(1) Projected progress with funding one-half current schedule

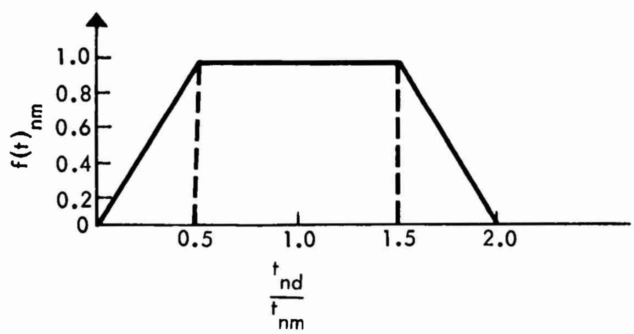
(2) Projected progress with funding on current schedule

(3) Projected progress with funding double current schedule

● Indicates the year in which technology objective is required for System m.

FIGURE 4. FDL Method Confidence Level Display Chart

g. Timing. The FDL method employs a timing concept that is similar to that employed in TORQUE to credit a task with achieving its objective in a time frame suitable for specific future weapon systems or technical goals. This timeliness function is shown in Fig. 5. It is based on the progress estimates contained in the confidence level relationships and the dates on which a technology is needed for incorporation into systems or fulfilling technical goals. From the confidence level relationship is taken the number of years that would be required under given funding rates to achieve a (CL) of 0.8, the level necessary to ensure fit into the system or goal. As is shown in Fig. 5, the value assigned to $f(t)_{nm}$, the timeliness variable pertaining to task n with regard to its application to system m, depends upon how well the underlying funding rate matches the progress of the task to the time that it is needed.



t_{nd} The number of years required to achieve a (CL) of 0.8 in Task n with funding rates of d,

t_{nm} The number of years until a (CL) of 0.8 in Task n is required for its coupling into System m.

FIGURE 5. FDL Method Timeliness Function

h. Risk. The principal element of risk that is taken into account in the FDL method is the probability with which the output of a task can be incorporated into a weapon system, given the confidence level to which the task has developed. This probability, P_n, is directly related to the confidence level values, $(CL)_n$, as shown by the right vertical scale in Fig. 4.

4. Constraints

Three primary types of constraints are incorporated into the FDL method. The first restricts the total amount of funds that can be expended in any one budget year of the program. The second limits the amount of in-house engineering manpower that can be used in the scheduled tasks for the next year. The third similarly restricts the amount of contract engineering manpower that can be used in the same time period.

A fourth type of constraint is used strictly for computation purposes. Although it is the main source of the large number of inequalities in the resulting computer model, it in no way has anything to do with the substance of the Exploratory Development allocation problem. Because a number of discrete resource levels may alternatively be allocated to any one task, this constraint is introduced for each task to prevent the computing algorithm's choosing more than one resource level in such a way that a larger amount than has been engineered is recommended for a task.

5. Decision Algorithm

The factors and analytical components described above are synthesized in the FDL method to develop a measure of value that is attributed to a task when it is funded at a specific level.

V_{nd} = value attributed to task n when funded at level d

$$= \frac{\Delta P_{nd}}{\overline{P}_n} \sum_{m}^{M} D_{nm}\ f(t)_{nm}\ b_{nm}\ S_m + \frac{\Delta (CL)_{nd}}{(\overline{CL})_n} \sum_{k}^{K} f(t)_{nk}\ b_{nm}\ T_k$$

where ΔP_{nd} = the change in P_n over the next year due to the funding rate d

$\overline{P}_n$ = the level of P_n at the beginning of the program year

$(CL)_{nd}$ = the change in $(CL)_n$ over the next year due to the funding rate d

$(CL)_n$ = the level of $(CL)_n$ at the beginning of the program year and all other variables are as defined in the above text.

Total value of the Lab program of Exploratory Development tasks is accumulated in the following function.

$$\text{Total Value} = \sum_{n}^{N} \sum_{d}^{D} V_{nd} X_{nd}$$

where X_{nd} = 1, if task n is funded at level d.

The decision algorithm consequently consists of choosing the X_{nd} is such a way to maximize the total value subject to the following constraints.

$$\sum_{n}^{N} \sum_{d}^{D} O_{nd} X_{nd} \leq \text{Available contract engineering manpower,}$$

$$\sum_{n}^{N} \sum_{d}^{D} H_{nd} X_{nd} \leq \text{Available in-house engineering manpower,}$$

$$\sum_{n}^{N} \sum_{d}^{D} F_{nd} X_{nd} \leq \text{Total available funds,}$$

$$\sum_{d}^{D} X_{nd} = 1 \quad (n = 1, 2, \cdots, N)$$

where O_{nd} = amount of contract engineering manpower required in task n when funded at level d

H_{nd} = amount of in-house engineering manpower required in task n when funded at level d

and F_{nd} = the funds that will be expended on task n when funded at level d.

In the original formulation of the FDL method a linear programming algorithm was used as the search and decision routine for the selection of the tasks to be included in the Exploratory Development program (Ref. 14). However, because that was judged to be too expensive, a specialized decision rule was devised and coded in 1968. The latter procedure is based primarily on the ratio of the military "utility" to the dollar cost for each of the alternative resource levels specified beforehand for each task (Ref. 15).

E. CORNELL AERONAUTICAL LABORATORY METHOD

Under contract to the U.S. Army Materiel Command, the Cornell Aeronautical Laboratory (CAL) reported in 1965 on a quantitative method that it had devised to guide the allocation of the Exploratory Development effort (Ref. 16). The starting point of this method is the Army's Qualitative Materiel Development Objective (QMDO), describing the general characteristics of a new weapon system. Proposed QMDOs are decomposed into technologies and tasks, for each of which an assessment is made of the risk of success. The budget available for Exploratory Development is allocated among the tasks in a manner that attempts to take into account the importance of the QMDOs the tasks support, the increase in the chance of success of the QMDO if the task is included in the program, and the cost of the task.

1. Primary Objective of the Method

The primary objective of the CAL method is to choose the set of Exploratory Development tasks that has the maximum expected "value" to the Army <u>and</u> that can be funded within the budget available for the next program year.

2. Control Variables

The principal control variables in the CAL method are the tasks that are to be undertaken in the Exploratory Development program. While control focuses first at the level of the development tasks, it ultimately determines the weapons that will be developed and the particular development strategy that will be followed in the program.

3. Factors and Their Relationships

a. Value Measure. The measure of value that is to be maximized appears to be a scaled unit of a personal or subjective indicator (possibly averaged over a number of subjects) of the "essentiality" of the various candidate equipments to the Army. The precise meanings of "value" and "essentiality" are not completely clear in the report; however, the vagueness of these concepts is recognized and their measurement is left to further study.

b. Operational Requirements. In the formal structure of the CAL method, no direct reference is made to the operational requirements of the Army.

c. Weapon Systems. The overall weapon system concept incorporated into the CAL method is the QMDO or Qualitative Materiel Development Objective. The QMDO is "a statement of a Department of the Army military need for developing new materiel, the feasibility or specific definition of which cannot be determined sufficiently to permit establishing a qualitative requirement" (Ref. 17).

As pointed out above, little has been done in the development of the method to resolve the measures of "essentiality" or "value" that are to be applied to the QMDOs. This was left to later work.

As the method is formulated, however, the QMDOs are proposals to which the Exploratory Development effort may be applied. Insofar as that effort is not limitless, the QMDOs compete with each other for implementation and, in that sense, are substitutes for each other even though they may not all fulfill similar functions.

Each overall weapon system concept, in turn, is decomposed into a set of subsystems or materiel concepts which describe

> ...the devices or items envisioned as being necessary to meet the objectives and requirements of a QMDO. Associated with each materiel concept is a set of critical performance parameters which are quantified expressions of the essential factors characterizing the performance required of the materiel concept. All materiel concepts for a given QMDO are considered necessary in meeting the QMDO (Ref. 16, p. 15)(emphasis added).

In other words, all of the materiel concepts in a QMDO are strict complements to each other.

d. Technologies. Each subsystem or materiel concept in the CAL method is conceived as being possibly implemented by any one of a number of composites of technologies. Each composite is formulated into a technical approach to the materiel concept which details the technological advances that must be made for its completion. For any single materiel concept, there is a menu of technical approaches that describes the

> ...proposed alternative methods or techniques to satisfy the Materiel Concept. A Technical Approach can have one or more Major Barrier Problem Areas associated with it which must be overcome by accomplishing proposed research and exploratory development tasks in order to establish the feasibility of the Technical Approach (Ref. 16, p. 15).

Technical approaches, therefore, can be considered substitutable for each other to satisfy a materiel concept; in this case they are strict substitutes, the completion of any single one supporting a materiel concept making the latter feasible.

e. Development Tasks. The specific work content of each technical approach is spelled out in terms of development tasks, time-phased Research and Exploratory Development efforts.

> ...Although a Task may be further subdivided into Subtasks, the Task is considered the lowest element of the QMDO Model Structure since it is the element which is funded as well as the one which furnishes the basic data for QMDO planning analyses and synthesis. Associated with each Task is one or more technical goals which represent the objective of the Task (Ref. 16, p. 16).

Each task is characterized also by the pattern of resources that is used in its execution. These resources are spelled out in terms of the Army Materiel Command R&D Field Establishments involved or in terms of other input measures considered relevant for budgeting purposes.

The development task structure of the CAL method couples Exploratory Development efforts specifically with individual materiel or system concepts. It preserves the identification of the tasks and their technology objectives with the QMDOs they support.

The tasks making up a technical approach may need to be ordered according to some sequence where the outputs of one task may be the foundation of another task required for progress toward the feasibility of the technical approach. However, where the sequence may be chosen on the basis of other considerations, the CAL method proposes that the tasks be ordered according to decreasing values of the ratio, $\frac{\text{risk}}{\text{cost}}$, where risk is the complement to the task probability of success (described below).

Through the formulation of the tasks, some consideration is also given to the alternative development strategies that might be followed to achieve technical goals and materiel concepts. The resolution of the development strategy is a consequence of including among the eligible alternative actions parallel technical approaches and backup tasks for the fulfillment of any single technical approach.

f. Costs. For each task or technical approach, costs are tallied in two different ways: (1) the total funds that will be necessary to support the particular task in the next budget year and (2) the profile of the different resources that will be used to carry out the task work during the same period.

The fund requirements are the total money costs that will be incurred in the next budget year to carry out the work planned under any single task. This quantity is the sum of all costs associated with a task regardless of where or on what they are spent during the budget period.

The CAL method also makes provision for tallying individual resources that will be employed in a particular task throughout the budget year. In this case, each U.S. Army Materiel Command R&D Field Establishment is treated as a separate resource and the extent that any one of these might be employed to work on a task is accounted for separately.

g. Timing. The time-phasing of the various efforts included within any given task is the principal avenue through which direct consideration is given to the timing of the Exploratory Development program in the CAL method. Less directly, the specification of the weapon systems to be included among those eligible for development over the next budget year must also contain, at least implicitly, some consideration of the timing of their being made available.

h. Risk. The primary objective of the CAL method is to choose the set of tasks so as to maximize the expected "value" of the Exploratory Development program to the Army.

It is the expected value in the sense that the method takes into account explicitly the estimated probability of success of each task in the Exploratory Development work aimed at demonstrating the feasibility of the QMDO.

The probability of success, and consequently the expected value, of a particular QMDO is derived from the individual and compounded success probabilities of the various operations in the development process. The basic building block for this evaluation is the probability of success assigned the individual tasks. For a particular technical approach, the probability of success is the probability that all the tasks necessary to the completion of the approach will be successful. The success probability for a materiel concept is the probability that at least one of the technical approaches will succeed. In turn, the probability of success of a QMDO is the probability that all of the materiel concepts making up the QMDO will be jointly successful.

The expected value of a QMDO is, therefore, the product of the "essentiality" measure and the probability of success of the QMDO.

4. Constraints

Three types of constraints are considered in the CAL method: QMDO contraints, resource constraints, and the budget constraint.

Provision is made in the structure of the model for the analyst to specify whether a QMDO must be in the final program or whether its inclusion can be elected. If a QMDO must be in the program, a QMDO constraint is devised to express the condition.

If prior policy determinations have been made to support the various Materiel Command R&D Field Establishments at no less than some minimum levels of effort, resource constraints are used in the analytical framework to ensure that support. Basically, such a constraint tallies the amount expended at a particular field establishment by all of the tasks included in the program and prevents the sum from totaling less than the chosen floor level.

The budget constraint ensures that the total costs incurred to fulfill the chosen tasks will not exceed the funds available for the Exploratory Development program.

5. Decision Algorithm

The factors that are taken into account in the CAL method are structured for deciding the budget allocation in a fashion that can be represented by the diagram contained in Table 4.

To choose the program of technical approaches (and consequently the first-year tasks) to be undertaken in Exploratory Development during the next budget year, the CAL method uses a rather simple procedure. However, it does involve extensive computations.

This procedure begins with the program that includes all of the technical approaches of all the QMDOs. It subsequently eliminates individual technical approaches on the basis of increasing values of the ratio, (change in expected program value)/(change in total program costs), associated with the elimination of individual technical approaches. Individual technical approaches contribute to the expected value of the program to the extent they contribute to the probability of success of the related QMDO. Also, if the elimination of a technical approach reduces to zero the probability of success of a materiel concept, the remaining value of the supported QMDO is eliminated.

TABLE 4. CAL METHOD FRAMEWORK OF FACTORS TAKEN INTO ACCOUNT

QMDOs	Materiel Concepts	Technical Approaches	Tasks Scheduled by Decreasing $\frac{\text{Risk}}{\text{Cost}}$
		TA_{111}	$\{TK_{1111}, TK_{2111} \cdots\}$
	MC_{11}	TA_{211}	$\{TK_{1211}, TK_{2211} \cdots\}$
		⋮	
$QMDO_1$	MC_{21}	TA_{121}	...
	⋮	TA_{221}	...
		⋮ ...	
	MC_{12}		
$QMDO_2$	...		
	...		

Eliminations are carried out in order of increasing values of the ratio as long as they do not involve violation of a QMDO constraint or a resource constraint. Those eliminations that would violate one of the constraints are skipped.

The procedure is continued until the total costs of the resulting program are reduced to the funding available for Exploratory Development, that is, the total costs satisfy the budget constraint.

F. HERCULES METHOD

The planning staff of the Hercules Corporation has formulated a quantitative method to guide the allocation of its Independent Research and Development (IR&D) funding among proposed development projects. These projects are quite similar in substance to military Exploratory Development work. In this method, the products that are generated by the development projects are analyzed in terms of their marketability, technological content, the development work remaining to be done, the cost of that development work, and the risks involved with each of these features. Available funds are allocated to the development of the products that are expected to earn the most profits for the company.

To the extent that could be determined, the allocation determined by this method appears to act as the basic budget for company IR&D work. Exceptions can be taken with the allocation and changes made in it on the basis of considerations that could not be incorporated into its formal operation.

1. Primary Objective of the Method

The primary objective of the Hercules method is to choose the set of development tasks that can be financed with the company's IR&D funds and that can be expected to generate the maximum profits for the company.

2. Control Variables

The principal control variable in this method is the amount of funds that should be spent on specific development tasks within each technology.

3. Factors and Their Relationships

a. Value Measures. In the Hercules method, the value of the IR&D effort is measured in terms of the dollar sales and profits it will generate for the company. This value measure is fairly readily quantified. Although predicted profits from the development work may not be estimated easily, they correspond to accounting data that are regularly measured and recorded.

b. Operational Requirements. In the structure of the Hercules method, the concept that corresponds most closely to military operational requirements is the set of characteristics that the company's marketing organization attributes to each market in which the company wants to participate. In addition, the marketing organization identifies specific subsets of these characteristics to help delineate the features that should be incorporated in any company product for that market.

c. Weapon Systems. Two concepts in the Hercules method correspond to military weapon systems in the structure of the general model: (1) actual equipment and other products that embody the output of the development effort and (2) potential contract research support work for which the company might qualify as a result of the particular project. In both cases, the marketing organization must also relate these products to the markets in which they can be sold by estimating the potential sales volume of the company and its profit margin in these markets.

d. Technologies. Using the marketing estimates, the engineering staff determines the technologies that will be necessary to satisfy the mission requirements of the project's products. In the technology composition, two kinds of relationships are admitted among the different technologies. First, the engineers establish the independent technology requirements of the project. Second, within any single technology requirement, the engineers may identify a number of technologies that alternatively can fulfill the requirement. In this second kind of relationship, the alternative technologies are treated as perfect substitutes for each other. In the first relationship, the product is presumed to be composed of strictly complementary technology requirements.

e. Development Tasks. Besides setting out the technological content of the project, the engineering organization estimates the nature of the development work that must be completed in each technical area to satisfy the project. Specifying these basically resolves into delineating the development tasks that must be performed and the technical goals of those tasks.

The company's research organization reviews the development tasks to estimate the feasibility of the technical goals. It also is charged with the responsibility to identify any other company-funded work or work being done outside the company that can be drawn upon to facilitate the development work that must be done.

f. Costs. The company's research organization also has the responsibility to estimate the funding that will be required to fulfill the technical goals of each development task in a technology. For each task a series of funding estimates is made, the different funding levels corresponding to different probabilities of success that the goal will be achieved within the specified time allowance.

g. Timing. The Hercules method incorporates into its allocation procedure consideration of the timing of the development work both in terms of the marketing of its products and in terms of the time needed to achieve a technical goal. In estimating the sales volume and profitability of any product resulting from a development project, the marketing organization must estimate the date by which the introduction of the product must be made to capitalize on the market available for it. This date, in turn, establishes when the technological development work must be completed to permit successful innovation of the product.

On the other hand, the research organization must estimate the relationship between the pattern of funding that might be devoted to a specific development task and the time that would be required to achieve a reasonable level of the technical goal.

h. Risk. The sources of the riskiness of a development project are introduced at several points in the structure of the Hercules method. The marketing organization's estimates of the sales volume and profitability of a project's product are made in terms of the probabilities with which the specific levels are expected to occur. In other words, the marketing organization must specify the probabilities that it believes applies to the actual outcome of alternate sales volumes and profit margins for a particular product when it is marketed.

In specifying the technological composition of the product of a development project, the engineering organization is also expected to estimate the probability that new research must be done in each technology to satisfy the project.

Last, the research organization must set the probability that the technical goal of a development task will be achieved within the allowed time under any given funding pattern for the task.

4. Constraints

The only constraint that is imposed in the method is that the program of development tasks must be devised within the given budget of IR&D funds.

5. Decision Algorithm

All of the analytical features of the method, for all the proposed development projects, are integrated into a single mathematical function that is used for computing the allocation of the IR&D funds.

$$\sum_j (WV)_j = \sum_j (RF)_j (PS)_j (PF)_j (PG)_j (PC)_j$$

where $(WV)_j$ = the weighted value of project j,

$(RF)_j$ = the probability that project j will be ready by $(YP)_j$, the necessary completion date, given the technology composition of the project and the development requirements of the technologies. In turn, $(RF)_j$ is a function of $(PR)_{ij}$, the probability that the research on technology i for project j will be completed by $(YP)_j$.

$(PR)_{ij}$ is a function of X_i, the dollar expenditure on technology i.

$(PS)_j$ = the total sales volume of the project output,

$(PF)_j$ = the company margin on project j,

$(PG)_j$ = the probability that the market will develop as expected,

$(PC)_j$ = the probability that the company can capture some share of the expected market.

The algorithm used in the method is basically a routine for searching the number of alternative allocations of funds among the technologies to find the one with the maximum expected profit payoff. The procedure follows an approximation method whereby a shift of funds from one technology to another is tried. The effects of such a shift are traced through the probabilities of the technology requirements being fulfilled to the expected profit values of the relevant projects.

G. ARMY MISSILE PLAN

The Army Missile Plan is generated by the Future Missile Systems Division of the Army Missile Command. The procedure for organizing the plan has been under development for a few years and has reached a point at which implementation becomes feasible.

Figure 6 shows the general flow of the materials prepared in the development of the plan. Unlike the methods described above, the Army Missile Plan does not employ a formal mathematical optimization procedure to determine the allocation of development resources among the technologies. It consists basically of setting out systematically and visibly the technological improvements and resources that would support projected weapons requirements. In this way, the plan provides information on a continuing basis for formulating Missile Command programs in Research, Exploratory Development, and Advanced Development.

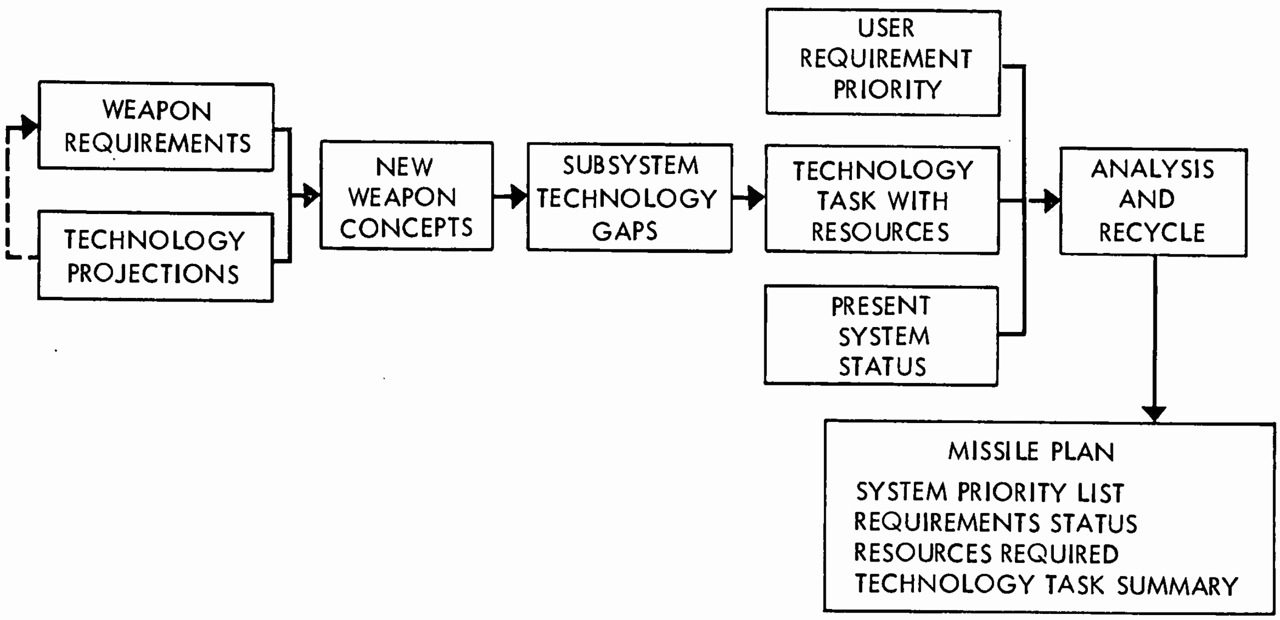


FIGURE 6. Army Missile Plan Procedure

1. Primary Objective of the Method

The primary objective of the Army Missile Plan is to show the time-phased set of development tasks and resources that would support weapons concepts proposed for future deployment within a specific scheme of priorities.

2. Control Variables

Because the plan is largely an information system without provision for some kind of optimization procedure, it is not clearly structured from the point of view of a decision maker who has discretion over a primary set of control variables. However, the general weapons concepts and the funding requirements of the technological tasks play pivotal roles in the planning procedure.

3. Factors and Their Relationships

a. Value Measures. The Missile Plan does not utilize a simple single measure of value to depict how well a particular course of action under the plan would achieve its primary objective. Of course, its primary objective is not set out in a fashion that its satisfaction can be readily measured by a cardinal metric.

The plan procedure does use, however, a set of concepts to assign priorities to the weapon systems that the development work is to support. It also uses criteria to assign ordinal ratings to the specific technological tasks that would be performed in the developmental effort. Both the priorities and ratings contribute to the establishment of task rankings that serve a purpose similar to other value measures.

b. Operational Requirements. Army operational requirements are introduced into the planning procedure through a number of documents generated by the Combat Development Command. These include the Qualitative Materiel Development Objectives (QMDO), Qualitative Materiel Requirement (QMR), Advanced Development Objective (ADO), Proposed Qualitative Materiel Development Objectives (PQMD), Proposed Qualitative Materiel Requirements (PQMR), and Draft Proposed Qualitative Materiel Development Objectives (DPQMDO). Each document describes fairly generally the military need for some new item, system or assemblage that will aid the Army in fulfilling its various missions. These user requirements are derived from Army plans that indicate the time period in which it would be desirable to introduce the new item into the force structure. Fifteen such requirements were used to derive the 1969 Missile Plan.

c. Weapon Systems. On the basis of the operational requirements, the Missile Command Advanced Systems Laboratory and/or industry developed a number of weapon system concepts. For the 1969 plan, 70 weapon systems were proposed to fulfill the 15 statements of requirements.

The relative priority of each of these weapon systems is set in terms of the target date on which the system should begin its Contract Definition Phase (CDP). This date is established on the basis of three factors: (1) the user's priority for the system as evidenced in the Combat Development Command Management Information System, (2) the timing of re-buys or planned phase-outs for the existing weapon system that currently fills the general role, and (3) the possible timing of any new technological advance that should be available for the CDP of the weapon system.

d. Technologies. The technical laboratories of the Missile Command and the Munitions Command determine the technological composition of weapon system and subsystem concepts. They then go on to estimate the current state of the relevant technologies and the advance that would be necessary to fulfill the concept designs.

Besides the operational requirements that give rise to specific weapons concepts, some user requirements are stated in terms of general functional capability that might be introduced into current or future weapons or used to support them. The technological components of these requirements are also established at this stage of the planning procedure.

e. Development Tasks. In the process of estimating the technological advance that would be necessary to fulfill the designs of the proposed weapons, the technical laboratories also prepare a plan of research tasks to achieve the technological advance. These tasks are planned in terms of the number of years that will be necessary to achieve the technical advance involved, the stage of development into which the work will fall in each year, and the schedule of resources needed.

Ratings are assigned to these tasks. A rating of I indicates that the task is critical to the fulfillment of the weapon concept objectives. A rating of II is assigned to tasks that have a high potential of technical advance but are not absolutely essential to reaching the weapon concept objectives. Marginal tasks having both a low potential and contributing little to specific weapon concepts are assigned a rating of III.

f. Costs. At the same time that they prepare the plan of research tasks, the laboratories also estimate their funding and manpower requirements.

g. Timing. Each research task and the corresponding requirements for funding and manpower are planned with timing patterns that will satisfy the original target date set for the contract definition phase of the specific (or earliest) weapon system they are to support. The target date for the contract definition phase is set in the first instance for each weapon system on the basis of the priority of the weapon and the "critical" development task planned by the labs. This task is absolutely essential to the development of the weapon, and the estimate of the time required to achieve the associated technical advance sets a limit on how soon contract definition can progress. The timing of all the other tasks linked to a weapon system is then rearranged to dovetail with the target contract definition phase date.

h. Risk. There is no provision in the Army Missile Plan for assessing and taking into account the chance of success of the individual tasks or the probability with which the necessary technological advances will be made. The tasks, their resource requirements, and their timing are set out as though they will all turn out as planned.

4. Constraints

Inasmuch as the plan sets out the technological development work that should be done to support new weapons concepts derived from independent statements of operational requirements, it does not incorporate explicitly any resource or political constraints on that development work. However, when the plan is subsequently used in the programming process to determine the allocation of Exploratory Development funds, the total budget available is treated as an external constraint.

5. Decision Algorithm

The development tasks worked out in the planning process are grouped according to common technological features and arrayed on the basis of the ordinal ratings assigned them in the labs and the priorities of the weapons in which they will be used. The recommended budget allocation is then derived by distributing the available funds down the array, beginning with the highest rated work, until the funds are exhausted. The lowest rated work supporting weapons concepts farther in the future or marginally useful to the planned weapons is the last to be funded and is postponed if the higher rated work absorbs all the funds. No formal mathematical optimization procedure is used.

H. AIR FORCE DOL PLAN

In 1969, the Air Force Systems Command Directorate of Laboratories (DOL) began to develop a method that it hopes will be used by all Air Force Laboratories to plan their programs in the Exploratory Development and advanced development categories. The resulting method is less quantitative than the others; however, it attempts to link explicitly the development plan to the Air Force systems concepts that have been projected for the future. The general outline of the development of the plan is contained in Fig. 7.

The Air Force Flight Dynamics Laboratory, which attempted the experimental application of TORQUE to its program in 1968, is one of the labs within this Directorate.

1. Primary Objective of the Method

The primary objective of the DOL method is to devise laboratory programs in Exploratory Development and Advanced Development that support the weapons systems projected for future deployment by the Air Force.

2. Control Variables

Inasmuch as the DOL method does not attempt to allocate the development budget with precision, it does not have control variables as such. However, the analysis of the plan does recommend a set of development projects and tasks that should be undertaken to support the future systems. Consequently, the recommendations of tasks serve the same purpose as control variables.

3. Factors and Their Relationships

a. Value Measures. The DOL method does not explicitly use any measure of value or scheme of priorities.

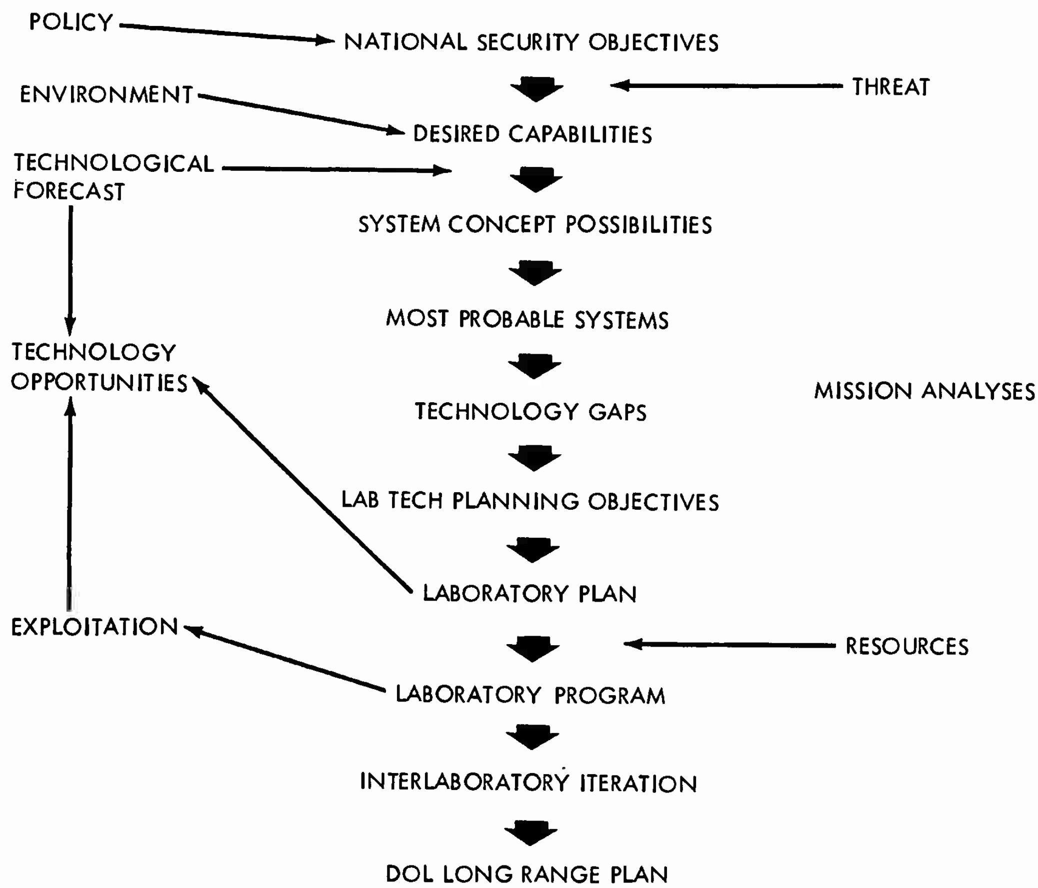


FIGURE 7. Air Force DOL Plan

b. <u>Operational Requirements</u>. For present planning purposes, DOL uses 13 desired capabilities in the same capacity as operational requirements. Desired capabilities are incorporated into the Technology Planning Guide as descriptions of the capabilties that are necessary to accomplish the missions and submissions assigned to the Air Force. The evolution of each capability is spelled out for a number of years into the future by five-year intervals, each interval depicting a step change.

As shown in Fig. 7, these operational requirements are derived from more basic statements of national security objectives.

Interestingly, the 13 desired capabilities that are used are the same as those used in the experimental application of TORQUE (cf. Fig. 11, in Chapter IV).

c. Weapon Systems. For each increment in an operational requirement, the Air Force Systems Command identifies a number of system concept possibilities and the most probable systems; AFSC also breaks out the system characteristics and pertinent performance data as well as critical subsystems and subsystem requirements. To carry out this analysis, AFSC consults with the various operating commands that would deploy these systems.

d. Technologies. Along with the AFSC, the different technical laboratories specify the technical goals that compose the subsystems of the projected weapons. For example, they would specify the desired specific fuel consumption (SFC), thrust/weight, thrust, etc., for the propulsion of a large subsonic cruise aircraft. From these goals, the labs identify the gaps in technology that must be filled. Similar technical goals are compiled into Technical Planning Objectives (TPOs) for each lab.

The development work that must be done to support a particular future system can be displayed in terms of the TPOs. In turn, the TPOs serve as focal points for the specific elements of work. Each Technical Planning Objective details the approaches that will be taken to fulfill the technical goal and the milestones that management can use to measure progress in the work.

e. Development Tasks. Each Technical Planning Objective in a laboratory consists of a number of basic work units called technical efforts. For organizational and planning purposes, these technical efforts are grouped into tasks according to the commonality of their technical goals. Tasks, in turn, are also grouped into projects. Finally, projects in similar technical areas are combined into the program elements that make up the Exploratory and Advanced Development program categories.

f. Costs. In describing the technical efforts that would be undertaken in a particular Technical Planning Objective, the laboratories must also incorporate a resource summary estimating the funding requirements of the technical effort.

g. Timing. The time pattern in the evolution of the desired capabilities is the principal avenue by which the timing of the development program is established. This time pattern displays discrete steps in the projected capabilities by five-year intervals. These changes drive the new systems that must be deployed in the different time frames and, consequently, the time pattern of development that must be accomplished to support those systems.

h. Risk. The DOL method makes no provision for the technical, cost, or timing risks that may characterize individual technical efforts or combinations of those efforts.

4. Constraints

The DOL method does not explicitly consider any special constraints that should be applied to the pattern of technical efforts it might recommend.

5. Decision Algorithm

Inasmuch as the DOL method does not attempt to allocate the resources available for implementing the development program, it does not use a set of rules for choosing a preferred set of technical efforts.

I. ARMY RESEARCH PLAN

The Army Research Office publishes the Army Research Plan biennially. This plan evaluates the balance of the Army's Research and Exploratory Development programs and provides general guidance to the field agencies on the shifts that might be made in their programs. The plan does not attempt to devise precise allocations of the related program budgets. It is essentially a management information system based on case studies that summarize important factors for each research and technology area. From these factors, it derives its recommendations on shifts in program emphasis.

1. Primary Objective of the Method

The primary objective of the Army Research Plan is to recommend shifts in the Research and Exploratory Development programs that respond to the long-range concepts, operational requirements, materiel and nonmateriel objectives projected for the Army.

2. Control Variables

Although the Army Research Plan does not attempt to control the programs precisely, it does recommend shifts in the funding patterns among the elements and subelements of the program. Consequently, it is formulated in a way that conceives funding of the program elements as the principal instrument of control.

3. Factors and Their Relationships

a. Value Measures. The Army Research Plan employs three types of value measures. First, it uses a scheme of priorities that expresses the relative importance of the operational requirements. Second, it uses a subjective measure of the contribution a technology makes to an operational requirement. Third, it also uses a measure based on the analyst's judgment regarding the timely progress of a development effort toward its technical goal under current funding conditions.

b. Operational Requirements. The Army Research Plan procedure derives operational requirements from three sources:

1. The Combat Development Objectives Guide (CDOG) contains 56 Operational Capabilities Objectives* approved by the Department of the Army.

2. The CDC Army 85 Concept Study lists a set of operational requirements.

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*An Operational Capability Objective is defined as "A Department of the Army approved description of an operational capability desirable of achievement in a specified time frame 10 or more years in the future. An OCO is responsive to envisioned future operational concepts, within constraints of probable technological capabilities. OCOs taken together provide a comprehensive goal to planners of doctrine, organization, tactics, logistical support and development, and provide guidance for research and, together with QMDO, for exploratory development." (Ref. 17, p. B-2)

3. The Army Strategic Plan describes a number of objectives that provide guidance for materiel and nonmateriel development efforts.

Each of these documents also assigns measures of the relative priorities that it recommends be given to its requirements.

c. Weapon Systems. The plan does not treat weapon systems explicitly or at all link them directly to its analysis. However, one of the major references used for guidance in the development of the plan is the Army Long-Range Technological Forecast. Volume III of that document describes advanced system concepts, which include examples of the materiel systems that would be possible if certain technological capabilities were achieved and applied.

d. Technologies. The scientific and technical areas considered in the Army Research Plan are described in the Army Long-Range Technological Forecast. The Forecast attempts to extrapolate for a period of about 20 years the scientific and technological capabilities that are particularly relevant to Army missions and needs. It is oriented primarily to the physical sciences. Social and behavioral science research subjects are contained in the Department of the Army Behavioral and Social Science Plan for Military Operations in the Developing Nations.

The Army Plan appraises the ability of the ongoing Research and Exploratory Development programs to support the operational requirements in a two-step procedure. First, it uses a matrix to show the support that various efforts in the Research program provide the efforts in the Exploratory Development program (Fig. 8). A second matrix describes the relationships of the efforts of the Exploratory Development program to the operational requirements. For these purposes, the 12 program elements in the Research program category are the Research efforts; the 30 program elements in the Exploratory Development program category are the Exploratory Development efforts.

The project officers in the Office of the Chief of Research and Development make an entry in each cell of these two matrices to describe the technical relationship between the technical fields or between the technical field and the operational requirement. In the first matrix, this entry depicts the potential relevance of the research element to the Exploratory Development element. In the second matrix, the entry depicts the potential relevance of the Exploratory Development element to the operational requirement.

EXPLORATORY DEVELOPMENT ELEMENTS

RESEARCH ELEMENTS	1	2	3	4	5	6	7	8	9	10	11	12	13	14	. . .
1															
2															
3															
4															
5															
. . .															

OPERATIONAL REQUIREMENTS

EXPLORATORY DEVELOPMENT ELEMENTS	1	2	3	4	5	6	7	8	9	10	11	12	13	14	. . .
1															
2															
3															
4															
5															
. . .															

FIGURE 8. Matrices in the Army Research Plan

For both matrices, five levels of relevance are distinguished:

Blank = no application perceived
1 = minor application
2 = substantial application
3 = major application
4 = essential application

The matrix entries are based upon the subjective judgment of the project officers and represent an abstraction of complex considerations.

The project officers also write qualitative appraisals that elaborate on the content of the different projects and provide a rationale to support the matrix entries.

e. Development Tasks. For the Exploratory Development program, OCRD has designed a more detailed matrix relating the projects within each program element to the 56 operational requirements. The relevance entries in this matrix are averaged to derive the relevance entries relating the program elements to the operational requirements. At the level of greater detail, the project officers also take into account the accomplishments of R&D activities external to the Army to judge the relevance of the technical area to the requirement.

f. Costs. In the plan, the past and projected funding trends of the individual Research and Exploratory Development elements are thoroughly documented. On the basis of this information and a number of other considerations, the project officers make another entry in each cell of the matrices. This entry reflects their judgment on the adequacy of support being directed to the program element as it pertains to the particular application. A fivefold numerical classification scheme is used to describe the adequacy of the current level of funding:

1 - significantly underfunded
2 - less than optimal funding
3 - optimal funding
4 - greater than optimal funding
5 - significantly overfunded

In this case, optimal funding is the level of support that would provide a reasonable probability of achieving the particular technical goal on time.

Other factors taken into consideration in the appraisal of the adequacy of currently planned funding include:

a. The sensitivity of the rate of advance in the technical area to funding changes

b. The rate of advance in the technical area at planned funding relative to the advance needed

c. The relative "marginal utility" of increased funding

d. The adequacy of efforts outside the Army to meet needs in the technical area

e. The proximity of the "threshold level" in the technical area

f. The proximity of the point at which needed "in-house" capability will be lost

g. The availability of personnel, facilities, and equipment

h. The quantity of valid "unfunded requirements"

i. The number of acceptable but unfunded proposals.

As in the appraisals of the technical relationships, the project officers provide the rationale for their judgments on the matrix entries in qualitative written analyses.

g. Timing. The Army Research Plan takes into account operational requirements for a period up to 20 years into the future. Technological advances needed to fulfill the operational requirements are embodied in the technical projects, the timing of which is obviously driven by the time horizon of the relevant requirement. From the necessary dovetailing of projects, the project officers must determine whether the time pattern of funding for any project is suitable. For the purposes of the plan, primary emphasis is given to those efforts that must be carried out within the next one to five years.

h. Risk. At most, the Army Research Plan considers qualitatively the risk involved in the different development projects. In setting out the relationship of a technical area to an operational requirement, relevance is defined as "potential" relevance. This qualification is intended to recognize the risk involved in actually achieving the project goal as well as the uncertainty regarding the precise nature of the impact the technical advance would have on the operational requirement.

In the appraisal of the adequacy of the currently planned funding for a project, the criterion of "optimal" funding contains a consideration of risk. Optimal funding is the level that provides a reasonable probability of achieving the project goal on time.

4. Constraints

A number of constraints are introduced into the deliberations on the shifts that should be made in the pattern of Research and Exploratory Development undertaken. At least implicit consideration is given to maintaining some level of in-house capability in the different technical areas. Also, the plan is concerned with the total budget that is available to do development work within its time frame. Under the procedures of the plan, consideration must also be given to (a) the need for the Army to be generally involved in Research and Exploratory Development, (b) R&D activities being carried on outside the Army, (c) development work directed by the OSD and the JCS, and (d) special Army responsibilities in the field as executive agent for the Military Services.

5. Decision Algorithm

The Army Research Plan does not employ a set of precise mathematical rules to arrive at its recommendations on the emphasis and direction that should be given the Research and Exploratory Development programs. A small staff planning group interprets the appraisals and funding information provided by the project officers. The group analyzes this information, taking into account several other factors, some of which have been described above. Among these other factors are the priorities given the various operational requirements and the constraints discussed in more detail in the preceding sections. In addition, the group incorporates the appraisals and recommendations in the Army Research Council Report, the recommendations of the earlier Army Research Plan, and the several responses made to those recommendations.

Finally, the staff breaks the program elements into three priority groups. The first group includes those efforts the staff evaluates to be most in need of increased funding. The second group includes the efforts that also need increased funds but with a lower priority than the first group. The third group consists of the efforts whose funding is considered satisfactory.

Final review and approval of the group's conclusions and recommendations are made by the directors of the OCRD directorates.

J. ANOTHER SERVICE METHOD

One of the Services has experimented with another specially formulated quantitative method to devise the mix of projects that should be included in its Exploratory Development program. This method attempts to quantify the considerations given a number of factors that bear upon the allocation problem and to integrate them into a single index that the method proposes be used to guide the allocation of the available budget.

Experience with the method was short; the Service terminated its application after one year.

1. Primary Objective of the Method

The designers of the method have not addressed directly the principal purpose for which the method has been formulated. However, one might infer that the primary objective of the method is to devise a development program that best serves the pattern of operational requirements composing the overall mission of the Service.

2. Control Variables

The method uses as the principal instrument of control the amount of funds that should be allocated to individual development projects.

3. Factors and Their Relationships

a. Value Measures. The method employs subjectively determined weighting factors to measure the relative importance of the different operating requirements and the contribution of each technological advance to the operating requirements.

b. Operating Requirements. A set of 29 of the Service's existing general operating requirements were used in the method. Senior staff personnel assigned a weight, ranging from 1 to 10, to each requirement, reflecting its relative importance in the overall mission of the Service.

c. Weapon Systems. The procedure of the method does not require reference to a set of weapon systems that might be deployed in the future.

d. Technologies. The method groups the development work to be done into general technological areas. These areas, in turn, are related to the individual operating requirements.

e. Development Tasks. The method basically analyzes development tasks such as those reported on Form DD 1498. In the particular application 750 such tasks were considered. Each task sets out its technical objective. Those tasks with objectives that fit together in some way are combined into a project.

In the procedure of the method, each task is assigned a number of weights, each of which measures the impact of the task on a particular operating requirement. These weights range from 0.1 to 1.0, using interpolations of the following scale:

1.0 - critical to developing the requirement
0.7 - extends the current ability to fulfill requirement
0.3 - improves the current ability to fulfill requirement

In this analysis of the tasks, the method also determines the number of concurrent approaches that are being taken to the same technical objective.

f. Costs. The cost data used in the method consists of estimates of the funding that will be required to complete each project.

g. Timing. The timing of the technical work and the required funding is derived from the dates by which the operational requirements should be fulfilled. In the particular application, operational requirements to 1982 were considered. Technical objectives, development tasks, and funding time patterns were worked out to meet those requirements.

h. Risk. This method does consider the probabilities that the different technical objectives will be successfully achieved. Those probabilities are based on the probability of success of the individual development tasks. For an individual task, the probability of success is the probability that the effort will achieve the desired technological advance within the given time frame under the currently projected funding. Achievement of a particular technical objective requires only the success of at least one of the tasks undertaken in parallel toward that objective.

4. Constraints

The method employs two types of constraints on the patterns of development tasks that can be considered. The first constraint requires that some minimum level of in-house capability be maintained in particular technical areas. The second requires including among the funded tasks those that are specially sponsored or directed from outside the immediate program management.

5. Decision Algorithm

The method uses four steps in its algorithm to determine the preferred ordering of funding for the individual development tasks.

First, it calculates the total value, V_j, of the technical objective j.

$$V_j = \sum_i W_i c_{ij}$$

where W_i = measure of relative importance of operational requirement i,

and c_{ij} = contribution of technical objective j to operational requirement i.

Second, it calculates the expected value, EV_j, of technology objective j.

$$EV_j = V_j P_j$$

where P_j = the probability of success of technical objective j,

$$P_j = 1 - \prod_{k=1}^{n} (1-p_k) ,$$

p_k = probability of success of individual approach k,

and n = number of approaches taken in parallel to technical objective j.

Third, the method calculates the desirability index, D_j, of technical objective j.

$$D_j = EV_j/F_j$$

where F_j = funding required for completion of technical objective j.

Finally, the method orders the tasks according to descending values of their desirability indexes.

In the particular application, the allocation (actually, distribution of a budget cut) was accomplished by dividing the tasks into three equal groups. The top third was funded at the requested level, the middle third was cut the average cut required, and the bottom third was cut twice the average cut required.

IV. CRITIQUE OF QUANTITATIVE METHODS

In this chapter, the methods for allocating development resources are analyzed within the framework of the General Model set out in Chapter II. Each major feature of the models (primary objective, control-variables, factors, constraints, and decision algorithm) is discussed in turn.

This analysis has a number of purposes. First, it provides a setting for describing desirable characteristics of the formal quantitative features and planning procedures that should be employed in a methodology for allocating the resources. Second, it attempts to ascertain the internal consistency of the methods that have been reviewed in detail. Would the resulting allocations achieve the goals that the formulators of the methods have set for them? Third, it points out the extent to which the features of the methods contain or violate desirable characteristics of any methodology applied to the problem of allocating resources within Exploratory Development. Would the allocation generated by the method produce desirable results in the Exploratory Development program? Fourth, in the process of working at the above purposes, it attempts to assemble some evidence on the feasibility and advisability of using a particular quantitative method to determine the allocation of the Exploratory Development budget. At the extremes, what might appear to be good characteristics of a quantitative method may not be feasible or may be terribly complicated and costly. On the other hand, what might be feasible may not be desirable. That is, there might be little confidence that following the allocation generated by a particular explicit method may ultimately contribute to higher order defense goals.

Rigid criteria cannot be established for such a critique. Within the framework of the General Model, the development of some features of a specific quantitative method may be a matter of choice. In a particular instance, the analyst may be able to choose any one from a set of options to devise a method without prejudicing its quality. However, any specific choice may need to be consistent with choices dealing with other features of the method, and its development may need to satisfy a number of conditions to ensure good quality analysis.

The precise formulation of the method will depend upon (1) the special interests of the analyst or manager, (2) the kinds of information available, (3) the technical training of the analysts and managers, and (4) the costs incurred to compose and implement the method.

All of the allocation methods that were reviewed are quantitative to some extent. That is, they all use numerical expressions for at least some of the factors that they try to consider systematically. However, the extent to which they rely upon numerical measures of factors and apply formal mathematical procedures to those measures varies significantly among the methods. Frequently, for purposes of the analysis, the methods fall into two fairly consistent groups. One of these is referred to as the "more quantitative" methods. They generally assign numerical measures to all the factors that they consider to be important in the allocation problem and proceed to derive a single measure of merit for each proposed development project. These methods also formally calculate the precise allocation of resources that should be made to each project. The group consists of the Industrial Analog, TORQUE, NOL, FDL, CAL, Hercules, and Another Service methods.

The other group is referred to as the "less quantitative" methods. These methods generally do not try to assign numerical measures to some important factors. They leave the consideration of these factors primarily to the judgment of the decision maker who determines the allocation of resources among the proposed projects without formal, optimizing calculations. This group consists of the Army Missile Plan, the DOL Plan, and the Army Research Plan.

A. PRIMARY OBJECTIVE OF A QUANTITATIVE METHOD

1. Discussion

The primary objective specified for the quantitative method is extremely critical to the resolution of the resource allocation problem. If the objective is misstated or inappropriate, the programs generated by the method will, most likely, not promote the intended end results.

Because of the limited perspective of the DoD Exploratory Development planning context, the objective devised expressly for a quantitative method applied to it may not be a direct measure of DoD's national security goals. However, the objective must be properly devised to reflect the role delegated to Exploratory Development so that the allocations generated by the method will contribute to the broader Defense responsibility for national security. In other words, effective Exploratory Development planning, outside a completely comprehensive plan of all Defense-related activities, first requires sufficient delegation of responsibility and effective subdivision of objectives and incentives.

Insofar as several approaches may be taken to Exploratory Development planning, with equally satisfactory results, the objective of a quantitative allocation method may not be unique. That is, depending upon the approach taken to the planning problem, an appropriate objective might be tailored according to this limited phase of Defense planning.

If the allocations generated by the quantitative method are to support the development of weapon systems, the primary objective of the method must include some consideration of how the demand for progress in a technology is derived from the coupling of Exploratory

Development into the overall weapon development process.* If the magnitude of this derived demand could be quantified readily, it would measure the "value" of the progress in the technology as a component of one or several systems.

However, some formulations of the primary objective can circumvent to some extent the need for a complete solution to the rather difficult derived value problem. The scope of the analytical approach for allocating resources within Exploratory Development must be sufficiently limited if the problem is to remain at all manageable. Therefore, adequate precautions must be taken to ensure that the quantitative method used is consistent with the overall Defense objective to provide national security efficiently. Such precautions can take the

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*In contrast with the systems support approach to Exploratory Development planning, another approach might be taken using the accomplishments within each technology area as the express objectives of the planning method. One variation on this approach would be to develop a minimum cost program of Exploratory Development work to achieve specified values for the "pacing parameters" in each technology area. Similarly, with a fixed budget, the objective could be to devise a program that will maximize the value of the pacing parameter in a particular technology area while achieving specified values of those in all the other technologies. Further, the pacing parameters can be set at different values in a series of solutions to the method to trace out the marginal resource and "opportunity costs" of shifts in the profile of pacing parameter progress.

Generally, the pacing parameter requirements are developed, either explicitly or implicitly, from broader studies of systems. However, if a technology-oriented approach were adopted and a directly derived relationship between technology and Defense demands were not required, the pacing parameters might well become uncoupled from systems projections and be treated as objectives in themselves. Because such an uncoupling could lead to an expenditure of effort in areas that are far afield from Defense missions, the technology-oriented approach is not pursued further in this report (such efforts may be considered exploitive).

form of explicit (and judicious) assumptions or restrictions on the primary objective of the quantitative method reflecting the policies that arise in the broader context. For example, with <u>fixed mission goals</u> for Defense forces, the Exploratory Development objective might be to minimize the cost of developing the technologies of new weapon systems that fulfill those goals and achieve some minimum level of "cost savings" over current forces. Or, the objective might be to maximize the rate of return to "investment" in Exploratory Development, given the force missions, the technology configurations of new weapon systems, and the potential "cost savings" of alternative new systems over current forces.

Another approach to systems support planning would be to fix the mission goals, possibly at current levels, and the budget that can be expended in Exploratory Development. The objective then could be to develop those technologies that are components of new weapon systems <u>maximizing</u> the cost savings possible over current forces.

If future mission goals are "increased" over those that hold at present in such a way that no conceivable changes in the current force mix or force levels could fulfill the goals, a somewhat different approach is necessary. The approach would still be basically one in which a comparison of costs would be made among alternative weapon systems but, in this case, the alternatives would be all the <u>projected</u> weapon systems that could fulfill the goals.

The means by which Exploratory Development planning is coupled to the overall development-procurement-deployment process require much to be determined outside the Exploratory Development context. Mission goals, preferences among these, and the savings of some new systems over current forces or other new systems are the principal avenues for expressing some of these outside factors in the suggestions made above.

Depending upon the different development strategies that can be followed, the costs and the initial operating capability dates of new weapon systems can be varied significantly. Consequently, the primary objective should include some provision for evaluating the different time phasings that are possible. Such evaluation should make explicit management's time preferences for different technology progress streams and different expenditure streams.

The development of each new weapon system, the initiation of work in new aspects of a technology area, the choice of funding levels and the planning of project completion time involve some risk that original intentions will not be precisely fulfilled. In fact, in some conceptions, the principal role of research and development is the production of the knowledge that reduces risk to a range sufficiently narrow to justify procurement and deployment decisions.

Reduction of risk by more intensive or parallel efforts obviously consumes scarce resources. Consequently, a higher chance of success in some technology development is purchased at the expense of the probability of success or the level of progress in another technology. Such trade-offs affect directly the objectives of Exploratory Development. Therefore, explicit treatment of the risk conditions and management's risk preferences in the formulation of the objective would provide a basis for evaluating the possible substitutions in these dimensions.

2. Primary Objectives of the Reviewed Quantitative Methods

The primary objectives specified in the quantitative methods that have been reviewed generally fall into three classes. First, there are the objectives such as that adopted in the Hercules method that do not neatly represent the goals of the Defense Exploratory Development program. Second, some objectives, such as those specified for the Industrial Analog and the Army Missile Plan, are quite restricted in scope, depending heavily upon explicit consideration of decisions made external to the Exploratory Development planning process. Third, the objectives specified in many of the reviewed methods are quite broad in that they are directed at generating allocations of the budget for Exploratory Development that will maximize some measure of overall military value.

The particular primary objective specified in the Industrial Analog (follow the patterns of technological development exhibited by U.S. industry) is hardly appropriate for determining the allocation of the Defense budget for Exploratory Development.

The objective of research and development effort for American industry is commerical success. Commercial success is measured principally by the profitability of the enterprise but other indicators may also be important to the companies involved in this context, such as survival, company share in the market and changes in that share, sales growth, industry leadership, and an image of progressiveness.

These objectives are tenuously, if at all, related to the national security objectives of DoD. Consequently, the connections of commercial R&D funding practices and results to DoD R&D resource allocation and the efficient achievement of Defense objectives are remote, at best. In fact, with similar conviction, an opposite contention might be proposed that DoD imitation of commercial research and development funding behavior would have a perverse result on national security objectives.

Actually, there need be little concern over whether the company objectives in doing commercial research and development are consistent with the broader economic goal that its activity improves the overall performance of the economy. The operation of the markets for goods and services acts as an effective and impersonal test for the broader goal. Those R&D products that succeed in the market by lowering costs or satisfying a new range of demand contribute to the efficient performance of the economy. Those R&D products that are market failures do not improve the economy's performance and do not impose additional costs on the economy once the failure is phased out. The parallel production of successful products that contribute to the economy's performance and unsuccessful products that absorb scarce resources while being developed is the price that is paid for a continuous flow of "improvements" in a context of large uncertainties. However, once the products are developed, the market operation generates additional clear and decisive information without catastrophic results for the economy.

No comparable impersonal test exists for demonstrating that products of Defense research and development will contribute to the efficient achievement of national security goals if included in the military force structure. All manner of physical and operational testing can be devised and carried out on old and new weapon systems alike. However, the decisive test such as commercial products face when placed on the market can only be conducted in actual war conditions when repetitive testing of alternative weapon systems may hardly be possible and the consequences of failure may be a national catastrophe.

The primary objective of the Army Missile Plan is properly modest in scope. It sets out to generate an Exploratory Development program that will support operational requirements and weapons concepts that are limited, in the first instance, by policies determined in the larger planning context.

On the surface, at least, little quarrel can be made with the kind of primary objectives specified for the TORQUE, Naval Ordnance Laboratory, Air Force Flight Dynamics Laboratory, and Cornell Aeronautical Laboratory methods. These methods attempt to generate allocations of the budget for Exploratory Development that maximize the "military utility" attainable from this program. However, the suggestion of such an objective raises immediately two suspicions. First, how does the analyst go about measuring such heady stuff as "military utility"? This anticipates to some extent the analysis below of the value measures that are employed in quantitative allocation methods. For the present, it is sufficient to be aware that special care must be exercised in devising this measure and relating it to the Exploratory Development activities so that the extent to which they fulfill the primary objective is clear. Second, how can one be certain that in fact the "military utility" indicated for a particular allocation by the quantitative method is attainable? In applying the Hercules method, a company could measure the profits that actually resulted from the products generated in the recommended development program, without resorting to the data used in the method. In a method somewhat like the Army Missile Plan, observations can be made, after the recommended development budget has been used, on whether the projected weapon systems were actually developed and on the actual costs incurred.

In most of these methods, the factors that are taken into account and the relationships among them are so directly tied and interwoven with the function representing the primary objective that they are basically inseparable. However, the CAL method appears to be structured so that it can be readily modified to accept other objectives, some of which do not have the same pitfalls as those based on the "value" or "utility" measures utilized in the TORQUE, NOL and FDL methods. For example, inasmuch as it has provision for considering the risk involved in the outcome of development work, the CAL framework could be used to investigate the maximum probability of success that might be planned for a particular QMDO, given a fixed budget and specified levels of success probabilities for the other concepts. In this way, the analyst might generate a "menu" of Exploratory Development programs, each of which involves the same level of total expenditure but among which success in the development of some concepts is traded off for success in others. Such a procedure might be a richer way to have management reveal its preferences (or "essentiality" measures) for the various QMDOs.

Alternatively, the CAL method might be used to investigate the minimum cost that must be incurred to secure a certain probability of success for attaining feasibility of a specified program of QMDOs. In the expression of the primary objective, the probability of success for each QMDO might be equal to the others, or a preferred probability might be specified for each. Through such an analysis, an evaluation might be made of the costs that would have to be incurred to increase the success probabilities, or that are being incurred to increase the probability of success at the margin for any QMDO.

3. Conclusion

Obviously, the precise expression of the primary objective of a quantitative method for allocating the Exploratory Development budget is not uncomplicated. The mechanisms suggested above for coupling the primary objective of the method to the overall development-procurement-deployment process are not completely satisfactory. Besides the formidable quantification problems that must be overcome if they were to be incorporated into the objective, the measures used to express the coupling are not conceptually precise. For example, the potential cost savings of new weapon systems over current forces arise at any stage in the development-procurement-deployment process, not just in the Exploratory Development stage. Each stage presents its own allocation problem that must also be resolved, and as each is resolved, in a somewhat circular fashion it generates information that is useful to the other stages.

For the most part, the primary objectives of the quantitative methods reviewed are too broad in scope. While their intent is undoubtedly good and in the right direction, measurement of the extent to which they can be fulfilled is vague, at best, and their verification in terms of actually observed results that can be readily agreed upon is virtually impossible.

B. CONTROL VARIABLES

1. Discussion

The analyst can exercise some flexibility in the way he specifies the control variables within the formulation of the method. However, if the allocation method is to be useful for structuring the Exploratory Development program, the control variables used in the model should conform fairly close to management's conception of the first-order choices it must make. Obviously, the detail incorporated into the method may be somewhat finer than might generally concern the particular level of management involved. While the process is somewhat cumbersome and not symmetrical, detail can be aggregated without loss of significance. On the other hand, if the relevant tier of management is concerned primarily with the development of <u>technology</u>, the options in the planning method should not be formulated in a way that would give it the choice of <u>systems</u> that will be developed ultimately.

Within the present context of budgeting Exploratory Development, the analyst might use one of two types of control variables. With one type, the weapon systems themselves must be chosen. With the other, the systems are fixed in a general way and their precise technical compositions must be chosen.

If the systems must be chosen, they become the principal control variables in the method. They are chosen to fulfill some specified capability requirements or missions on the basis of the objective adopted. In turn, the technology developments that must be initiated to support these systems and the funds that must be budgeted for these technologies follow closely from the choice of systems.

In the other approach, the general weapon systems that will be developed are fixed, but the specific configurations of technologies composing the designs of the systems must be chosen. In this case, the principal control variables are the technology areas in which Exploratory Development should be undertaken. These choices can be stated either in terms of some critical parameters of the technology areas, indicating progress adequate for the proposed weapon systems, or in terms of the funds that must be allocated to the technology areas to ensure the required progress. In any event, more precise systems designs will follow closely from these decisions, and the recommended budgets of the technology areas will either be a direct output of the method or be directly derived from it.

Besides choosing the weapons systems or technology areas in which Exploratory Development work will be done, the program manager may also want to control as much as possible the calendar time that will elapse until any one effort is completed. By adopting different development strategies and incurring different costs, he may be able to change the time between the inception and completion of a project.

The program manager may want to be able to control to the extent possible the level of risk that he must bear regarding the performance, cost, or timing of any one Exploratory Development undertaking.

Provision for risk is an explicit recognition that the predicted outcome of any Exploratory Development effort should be expressed as a probability distribution. The manager's choice of a risk level gives him some control over the assurance he will have that the actual outcome will approximate the intended outcome. Of course, he may not be able to choose the level of risk for all features of the outcome simultaneously. Greater assurance of the technology performance characteristics may possibly be achieved only at a higher expected cost, greater cost risk, or both.

2. Control Variables of the Reviewed Quantitative Methods

With the notable exception of the Cornell Aeronautical Laboratory method, the first-order control variables of the methods reviewed are the funds that are to be devoted to individual development tasks or to technical areas. Of course, the tasks that will be undertaken and the level of effort expended upon them follow necessarily from that choice of the distribution of funds. The CAL method reverses that order somewhat. For it, the first-order control variables are the tasks that will be performed. These tasks are performed fully or not at all so that the funds allocated to any one cannot vary between zero and the total estimated cost of it.

These control variables appear to be the most relevant for the administration of the Exploratory Development program at levels of management concerned with the overall distribution of the budget. Also, at first glance, they appear to satisfy the concern expressed earlier that the scope of Exploratory Development planning should be properly delineated to reflect its somewhat restricted purview of the joint problem of weapon development, procurement, and deployment.

The control variables in the methods reviewed have at least two shortcomings. First, they omit some very important considerations that management must make. Second, they are frequently specified in a way that results in their determining some fairly remotely related aspects of the development process through their second-order effects.

Among the most glaring omissions from the considerations that management must make is the discretion it can exercise over the timing and the risks associated with the technical results of projects. Most of the discussion of timing and risk in Exploratory Development is consolidated below in sections under those titles. In the context of control variables, however, note should be made that none of the methods pay much attention to the extent to which management can control the timing of a task and the technical progress a task can achieve.

The second shortcoming is particularly evident in the formulation of TORQUE and the methods closely patterned after it. In these cases, the primary control is exercised over the funds allotted to the various development tasks. However, the particular configuration of tasks that is chosen by the budget allocation algorithm in turn determines the weapons that will be developed, the operational requirements that will be satisfied, and the missions for which new weapons will be developed. This is undoubtedly a much larger responsibility than anyone would want to vest in a method for determining the allocation of funds for Exploratory Development.

3. Conclusions

Basically, the control variables specified in the quantitative methods reviewed are unobjectionable. They reflect the first-order concerns and choices that must be made by management responsible for allocating the Exploratory Development budget.

The principal shortcomings of the control variables used result to a large extent from faulty formulation of the relationships of such factors as timing, risk, technologies, and value to systems, operational requirements, and primary objectives. These are discussed more fully below. As a consequence, the discretion exercised over the control variables of the allocation of Exploratory Development funds, in many cases, has much broader implications for factors that should fall outside the proper range of the matters determined in Exploratory Development.

C. FACTORS AND THEIR RELATIONSHIPS

The functional relationships incorporated into the allocation method are basically abstract expressions of the real conditions that must hold among the important factors in the problem. In effect, the factors and their relationships tally the questions that a proposed course of action must be able to satisfy to ensure that it is workable and that there is some reasonable chance for the intended results to actually occur.

From another point of view, the relationships can be considered as a set of checks on the connections among the inputs and outputs of the different stages of the R&D process. The purpose of these checks is to shape the planning-decision framework so that it reasonably describes and is consistent with the real counterpart operations of R&D to some level of detail.

As the critical link between the conceptual-analytical framework for planning and the actual occurrences, the relationships among the factors are an important determinant of the usefulness of the planning exercise. Obviously, if the functional relationships are inaccurate descriptions of the conditions that hold among the factors, the resulting plans are more unlikely to bring about the intended development outcomes. Also, if some important conditions that hold among the factors are not included in the set of relationships, the programs planned with the allocation method will probably generate technology developments at variance to those intended.

Individual relationships among the factors frequently defy ready classification by type or purpose. All of them generally tie together closely, and any distinction must be drawn on the basis of different viewpoints to the overall problem or on the basis of the different problem features formulated in the set. In the following discussion, a division of the factors and their relationships is used to emphasize the different problem features that are incorporated into the model through them.

1. Value Measures

a. Discussion. In the present context, value is an indicator of the extent to which a development task or action achieves its objective. The relevant relationships involving the value measure show the extent to which different levels of effort in the task achieve different levels of the objective. Depending upon the particular point of view adopted, the results, and therefore the value, of the development work may be measured in terms of outputs more or less immediately connected to the work. For example, for some purposes, the value of the development work might be measured in terms of the technological parameters it affects. In that case, outputs immediately stemming from the work measure its value. For other purposes, the value of the development work might be measured in terms of its contribution to the fulfillment of a particular mission or operational requirement. In those cases, results fairly far removed from the actual work measure its value.

For any single technological effort, therefore, there is generally a function that relates the relevant measure of expected results to the cost expended on the effort. A typical function is shown in Fig. 9; it was developed during discussions at the Air Force Rocket Propulsion Laboratory (AFRPL). It simply indicates that some investment is necessary before results of any significance are obtained; this is the "buy-in" point on Fig. 9. Once funding reaches this point, an increase in value will generally result from an increase in effort.

It is difficult to measure with reasonable confidence the value of most technical developments to their end products in operational defense systems.

A few examples of such analyses have been found. In HINDSIGHT (Ref. 4), estimates were made of the benefits realized from the introduction of two operational systems: the C-141 cargo aircraft and the AN/SPS-48 radar. A good example of a study of the value of non-Defense applied research is contained in Ref. 18, an analysis of gold recovery processes by the Department of Interior.

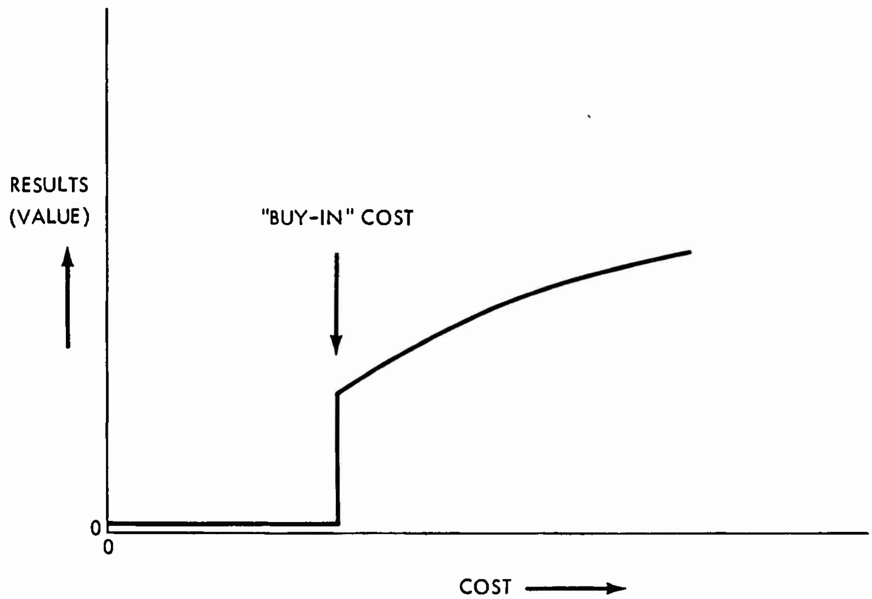

FIGURE 9. Typical Value-Cost Relationship

b. Value Measures in the Reviewed Quantitative Methods. Outside of the Industrial Analog and DOL methods which employ no concept of a value measure, three types of value measures are used in the quantitative methods reviewed. The first of these, the type employed in the Army Missile Plan and the Army Research Plan, is an ordinal ranking that depicts the priority of each development task according to its contribution to the weapon concepts devised to satisfy the various operational requirements. The second type of value measure, employed in TORQUE and similar methods, is a cardinal measure that attempts to quantify the contribution that completion of the development task would make to overall military utility. The third type of measure is the kind employed in the Hercules method, a fairly objectively estimated quantity measuring the profits that the company expects to earn from the commercial exploitation of the results of the development task.

On its own terms and within the limited objective of the method, the priority scheme used in the Army Missile Plan fulfills its purpose fairly well. Priorities are assigned in the first instance to the individual weapons concepts according to a number of criteria, and that linkage remains quite explicit throughout the remainder of the planning process. Moreover, these priorities are not subject to subsequent arithmetic calculations that treat parts of one ranking as if they are equivalent to portions of another ranking. Consequently, the value measure of the Missile Plan is quite visible to critics. Although it gives the appearance of being rigid in application, it is consistent, and it does not give rise to some of the serious problems that afflict supposed cardinal measures used in other methods.

The second type of value measure, which is employed in TORQUE and the NOL, FDL, and CAL methods, is an attempt to devise a cardinal measure of the contribution that a development effort would make to an indicator of overall military utility. In all of these cases, resort is made to a consensus of subjective evaluations of the value question by a number of analysts and policy makers. The basic rationale for collecting these subjective evaluations and combining them into the value measures that are finally used is the Churchman-Ackoff approximate measure of value (Ref. 12, p. 87).

Most of the problems that arise in the construction and application of these value measures stem from the particular circumstances surrounding the assignment of value numbers to other factors taken into account in the method. These are discussed in somewhat more detail under the headings below relating to those factors.

In general, these value measures suffer the same faults as the broad objectives whose achievement they try to gauge. First, because of their highly subjective nature, such value measures should prove to be virtually impossible to replicate. Second, insofar as they have no counterpart outside the analysts and policy makers who assign the numbers to the various factors the value measures cannot be verified in any real sense. In other words, there is just no way to tell whether the successful completion of a single development task or some set of development tasks actually contributes to "military utility" to the extent indicated by the assigned value measure.

The CAL method displays kinship with the TORQUE, NOL, and FDL methods on this point only in the proposal of a similar value or essentiality measure. The precise meanings of its "value" and "essentiality" are not made completely clear; much to its credit, the CAL effort points out the vagueness of these concepts and leaves their measurement to further study.

The third type of value measure is exemplified by the Hercules method which uses estimates of the profits that the company will earn from the successful completion of a development effort and commercial exploitation of its results. Replication of this measure would appear to be fairly easily accomplished, and verification seems to be no more than a matter of some careful and purposeful accounting. Besides having these desirable properties, company profits also probably suffice as a neat transformation of several, possibly complex, value measures into a single indicator of the extent to which the company's objectives are achieved by the development effort.

c. Conclusions. Obviously, the choice of the value measure used in the Hercules method depends upon the prior choice that should have been made about the primary objective of both the Exploratory Development program and the quantitative method devised to select the program. However, while the primary objective that is sought may be acceptable for general purposes of Defense planning, the value measure used to indicate the extent of the achievement of the objective may be quite inappropriate.

A value measure such as that used in the Hercules method just does not have a counterpart in Defense planning concepts, or at least those Defense concepts that are similar are not measurable. In this instance, Defense planning, as a whole, can be likened to a barter economy in which there is no mechanism for transforming the units of the numerous and highly diverse outputs into a single measure. Without a great deal of progress in this area, the value measure used in the Hercules method provides little guidance for devising the comparable factor in a method that could be applied to allocating the budget for Defense Exploratory Development.

Although more specific problems of the value measures employed in the TORQUE, NOL, and FDL methods are discussed below, a general objection to them is that they are extremely nebulous. They are necessarily so because of what they are purported to measure, vague expressions of overall military utility. The impossibility of verifying these measures and their particular assignment to specific development efforts makes their usefulness highly dubious, at best. Moreover, to anticipate some objections raised below, the application of the particular procedure adopted to synthesize these value measures does not make them proxies for a value measure paralleling the profit concept employed in the Hercules method.

Inasmuch as the inappropriateness of many of the value measures stems from the overly ambitious objectives set for the quantitative methods in which they are used, analysts should try to specify more modest objectives and value measures, at least at this stage of progress. Somewhat more modest objectives have been discussed above. Measuring the cost of a development effort or its technical completion should prove to be much more easily verified than any utility scale that has been used as a value measure. Moreover, the simplicity and directness of a priority scaling, such as that used in the Army Missile Plan, are highly desirable, especially if the scaling is not subjected to a number of subsequent arithmetic manipulations that obscure its limited meaning.

More intensive research should be undertaken on this factor. Any progress in devising appropriate measures of value for Defense planning would be helpful. The approach to measuring cost savings adopted in HINDSIGHT might be worthwhile to extend to situations in which the basic mission is changed. Approaches that would display the trade-offs among a number of measures of value should be examined as well.

2. Operational Requirements

a. Discussion. Operational requirements emanate from a joint consideration of the range of threats that might be made to the military security of the United States and the military capabilities that are needed to counter those threats. A uniform set of operational requirements could be defined for DoD-wide planning; probably less than 100 would suffice. Each operational requirement should give sufficient information for the systems designers who use them to understand the performance characteristics they must try to incorporate into any equipment.

Senior level personnel from the Services and the OSD should undertake the definition of these requirements so that they carry sufficient authority and uniformity to encourage their adoption. Definition of the requirements by such personnel might also prevent the development of an undesirable informal division of them among the Services where benefits of strict specialization are not particularly clear.

If there is unanimity on the composition of the threat to the military security of the U.S., the operational requirements should reflect the balanced goals that are to be satisfied simultaneously in some particular future period. Possibly more than one set of requirements could satisfy both these military goals and other national goals at the same time so that different sets might be specified depending upon the time period or other conditions considered.

Operational requirements can probably be developed from existing Service documentation of desired military capabilities such as OCOs, GORs, desired capabilities, etc. Currently the development of Service military capabilities often takes a long time. Figure 10 shows the steps in the development of an Army QMDO.

In any event, specification of the operational requirements should take place outside the planning of the Exploratory Development program. Proper definition of these requirements is one of the ways by which common ground rules can be imposed on the various stages of the overall development-procurement-operations process.

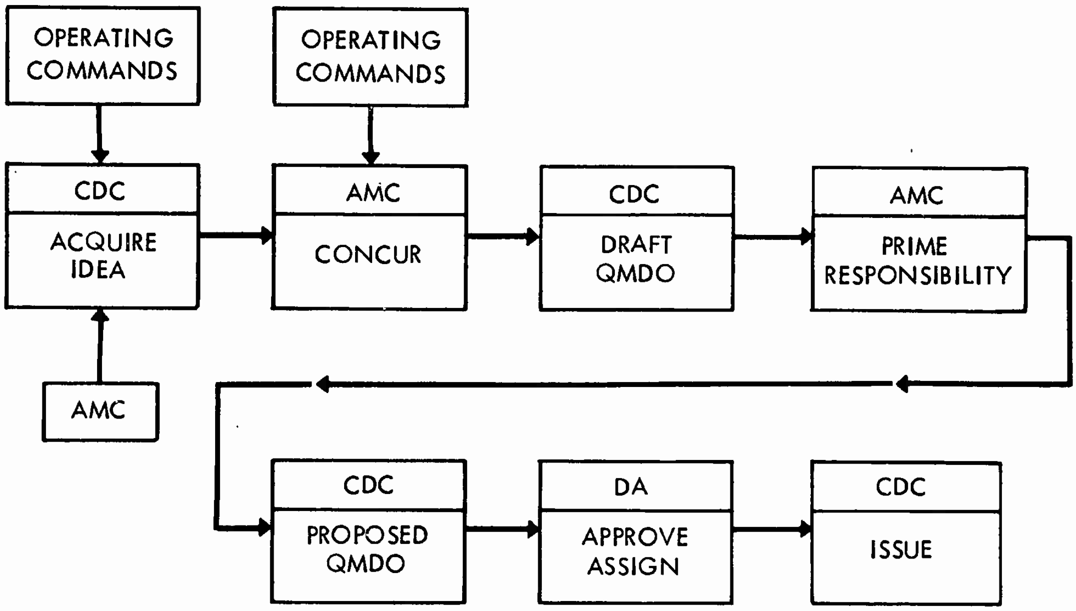

FIGURE 10. Requirements Procedure, Army QMDO

b. Operational Requirements in the Reviewed Quantitative Methods. All of the methods that were reviewed use some factor that parallels the concept of an operational requirement. For present purposes, the military requirements and the weights assigned them in the derivation of the value measure are of primary interest.

In an experimental application of TORQUE, a set of 13 operational requirements were developed for the Air Force (Fig. 11). The basic formulation of the TORQUE method calls for precise definitions of the missions that the Defense Department is expected to perform in support of national security goals and for a systematic clarification of the relationships among those missions. However, a problem can arise regarding analytical applications of the definitions if an attempt is made to assign measures of relative importance (value) to the operational requirements. When analysis calls for assignments of quantitative measures of value to the requirements, the properties of the

• GENERAL WAR	• DESTROY ENEMY STRATEGIC FORCES AND RESOURCES
	• DESTROY ATTACKING AIRBREATHING FORCES
	• DESTROY ATTACKING BALLISTIC MISSILES
	• DESTROY HOSTILE SPACE FORCES
• TACTICAL WAR	• CLOSE AIR SUPPORT
	• DEEP STRIKE/INTERDICTION
	• COUNTERAIR
	• SPECIAL AIR OPERATIONS
• POSTURE MANAGEMENT	• SURVEILLANCE/RECONNAISSANCE
	• COMMAND/CONTROL/COMMUNICATIONS
• GENERAL SUPPORT	• AIRLIFT
	• NAVIGATION AIDS
	• SPACE TRANSPORTATION

FIGURE 11. Desired Capabilities, Air Force

analytical method, the value measures, and the real counterparts of the definitions must be consistent. Analogously, the speed of an automobile cannot be gauged by a lineal measuring device alone; a timer is also required, and these measures must be integrated properly if they are to be used in an accurate display device.

Consequently, the originators of TORQUE recognized that the requirements must possess three characteristics: (1) they should be relatively stable in definition and importance over time, (2) they should be defined independently of actual and prospective technology developments, and (3) they should be independent of each other. The first two of these properties are necessary for the requirements to fit into any analytical or allocation framework. The first ensures that there is sufficient continuity in the problem structure that analysis can be performed, verified, implemented, and eventually tested for the correctness of the results. The second ensures that the goals themselves are not dependent upon the manner in which the development resources are expended. Such dependence would only lead to a circular planning process that would eventually become self-confirming. The third characteristic stems directly from the value measure that the originators recommend be applied to the requirements.

In the TORQUE procedure, one, and only one, relative weight is assigned to a particular operational requirement. For example, the one specifying the destruction of enemy strategic forces and resources might be assigned the highest weight, say 100, among the Air Force requirements. At the minimum, this unique assignment confounds two separate considerations: the importance of the general mission and the probable performance of the mission. Several gradations appear to be possible in the performance of this type of mission, depending upon the location of the enemy, the types of forces and resources that are to be destroyed, and the amounts of these forces and resources that are likely to be destroyed. The single measure of value for the mission results in different capabilities in these missions being treated as though they were equally important.

The TORQUE manuals recommend the application of the Churchman-Ackoff approximate measure of value to the operational requirements. It appears to generate the types of weights that could be used in the TORQUE "utility function."

The Churchman-Ackoff measure (cf. Ref. 12, pp. 87-91) is based on a special procedure for assigning value quantities to the occurrence of various <u>events</u>. Basically, it compares the events pairwise and in various (and any) combinations to solve for a consistent (but not necessarily unique) weight for each event that will preserve the rankings of the events in any combination. To fit this kind in measurement framework, the actual events must be of a special type. Logically, they must be able to occur simultaneously, and they must be independent of each other. If two particular events could not occur at the same time, they and their weights could not be combined for comparison with that of other events; therefore, the procedure for determining consistent weights could not be carried out. If two particular events were not independent of each other, the relative importance of their simultaneous occurrence would not be the same as the sum of their individual weights when they occur separately. Consequently, the assignment of individual weights through pairwise and combination event comparisons could not be done.

Although, in general, the operational requirements can be defined in any way that meets the needs of management or analysis, the properties required of the subject events for application of the Churchman-Ackoff measure must be met, or the procedure for assigning weights becomes virtually meaningless.

The consequences of these properties for the operational requirements and the TORQUE method in general are quite significant. First, because of their very broad definitions and specific contents, each of the requirements, as they currently stand, can hardly be treated as individual events. The achievements possible under any one, such as the Air Force desired capabilities listed in Fig. 11, are so diverse and variable that any specific combinations of such achievements cannot be taken to be alternative events of equal value. Would the destruction of a factory that manufactures ICBMs be the equivalent of destroying ICBMs deployed and ready in their silos? Both of these cases appear to fall under the one operational requirement, "Destroy Enemy Strategic Forces and Resources."

At the same time, however, breaking out separable events from the general requirement may only shift the source of difficulty with the measure for these purposes. The events so devised by definition must still correspond to real counterparts that are able to occur simultaneously, and these real counterparts must be practically independent. Such conditions can be extremely difficult to satisfy. And the independence requirement is particularly severe.

Independence of the requirements means that the fulfillment of any two of them jointly generates the same value as the sum of the values that would result from their separate fulfillment. This condition can be illustrated in terms of the requirements listed in Fig. 11. Taking two of the requirements, close air support and command/control/communications, three separate "events" are possible: (1) the Air Force supplies close air support with random sorties and strictly by pilot judgment, (2) the Air Force maintains a command/control/communications network, and (3) the Air Force supplies close air support combined with a command/control/communications network. If the requirements were independent, the value of Event 3 would be just equal to the separate value of Event 1 plus the separate value of Event 2. While the isolated use of close air support may supply some defense effectiveness and the isolated use of a command/control/communications network may generate some defense benefits, the joint application of these functions would appear to have a much greater effectiveness than a simple sum of their isolated benefits because they complement each other.

This problem is then carried through the remainder of the steps in the method that depend upon the weights assigned the operational requirements.

Although the terminology employed is somewhat different, the NOL and FDL methods rely upon conceptual constructs that are much like the operational requirements concepts used in TORQUE. These methods also propose the use of the Churchman-Ackoff approximate measure of value as the procedure that should be followed to assign importance weights to their requirements concepts. Consequently, their weighting schemes suffer the same deficiencies as those described above for TORQUE.

c. Conclusions. Obviously, the definition of operational requirements can be an extremely helpful step in the planning process. If carried out clearly and with precision, these definitions serve to break out higher order objectives into components that are more specific and operational. However, a number of problems can arise in the attempt to make operational requirements explicit. One of these problems is finding the proper level of personnel with expertise and perspective to set out the operational requirements so that the Services and OSD can agree on the content of a common set to be used by all elements of the Department of Defense. Another problem is the specification of an exhaustive set of requirements that will adequately cover all of the functions carried out in Defense. For example, the operational requirements set out for the experimental application of TORQUE by the Air Force and the QMDOs used by the Army do not appear to include items that express nonhardware types of objectives such as might be dealt with by behavioral sciences.

Another serious problem revealed in the reviews concerns the assignment of "weights" to the various operational requirements to form measures of "military utility." In some of the methods, the weighting was necessary to the operation of the allocation technique. However, the significance of the weights of operational requirements and the procedures for assigning them do not appear to be uniformly understood. For example, different weights might be taken to mean (1) the manager is willing to incur higher costs to fulfill one requirement compared to another, (2) the manager considers one requirement just absolutely more important than another by some scale measure, or (3) the manager would like to fulfill the defined operational requirement, if possible, before fulfilling others of lesser rank.

These meanings obviously confound a number of considerations dealing with both the importance of the requirements and the costs of fulfilling them. But even if the criteria of importance could be made precise, the problem remains that the method used to assign the weights pertains to a very special type of event whose features are not very closely matched by operational requirements.

3. Weapon Systems

a. Discussion. Devising weapon system concepts is another step in the procedure for planning Exploratory Development that moves from the more general military objectives to the more specific content of the technological advances needed. In this step, analysts try to design, more or less precisely, the hardware that could fulfill the operational requirements in some way.

Appraisal of the future impact of a technological advance depends heavily upon projections of the hypothetical systems that will utilize the technology. During the Field Survey some Service laboratory organizations were found to ignore clearly identified probable future systems; this did not seem to prevent high quality efforts in Exploratory Development. However, the existence of probable future systems in mind if not on paper usually became apparent in the course of discussions.

The responsibility for the development of the probable future systems is usually assigned to the System Commands in the Services; the laboratories, that ultimately manage the Exploratory Development effort, participate in the synthesis of probable future systems at a relatively low level. The Army Missile Command performs system studies both in- and out-of-house: recent studies include SAM D and the LAW (light antitank weapon) Workshop; future studies include TRAADS and MARS (multiple artillery rocket system).

Many examples of present ability to translate operational requirements into probable future systems have been found in all three Services. The Navy has probably advanced the art of presenting all probable future systems more than any other Service. The Navy Technological Forecast (Ref. 19) presents probable future systems and subsystems for the entire Navy. Earlier efforts within the Navy were centered in the Naval Air Systems Command with the publication of the Annual SMEADO (Selected Major Exploratory and Advanced Development Objectives) and the Naval Ordnance Systems Command ACORD. The field survey also found that three or four systems may typically describe most of the reasonable approaches for a single operational requirement and can be substantiated by good to fair systems analysis.

In the view of some of the Exploratory Development managers who have had probable future systems made available to them, there is an impression that the system characteristics change rapidly in comparison to the ability to reorient Exploratory Development programs.

During the field survey, it was also found that there was great variation in the quality of the systems analysis supporting the probable future systems.

A good systems analysis to meet an increased threat will compare the expansion of present systems, as well as consider alternatives in new development to satisfy needs. It will also consider operations and maintenance in arriving at the recommended probable future systems. Even in the relatively mature Army Missile Plan it is estimated that only about one-third of the candidate systems are substantiated by a high-quality systems analysis.

One way to deal with the interface between Exploratory Development and the overall sequence of development, procurement, and operations is through functional relationships among factors such as those pertaining to weapon systems.

In a quantitative method supporting systems development, functional relationships can be used to make explicit the assumptions that must be imposed on Exploratory Development from the larger context about (1) the performance characteristics of alternative weapon systems proposed to serve the same operations requirement and (2) the conditions that must hold among elements of different force structures and different force levels to satisfy the higher order military objectives.

It is possible that quantitative methods for allocating resources in Exploratory Development are suited to the more system-oriented Services like the Navy and Air Force but not to a doctrine-dominated Service like the Army. Such a conclusion might be based upon the efforts by the Army in 1967 to develop operational requirements that could lead to systems. This effort paralleled the one in the Air Force that ultimately led to the TORQUE experiment at AFFDL. It should be noted, however, that in our very limited field survey no such difficulty was reported, either in the fields of rocket propulsion or Army electronic components research.

b. Weapon Systems in the Reviewed Quantitative Methods. All of the quantitative methods reviewed rely upon weapon system designs, to some extent, as intermediate planning concepts to determine the technological advances that Exploratory Development efforts should try to attain. However, the ways in which the various methods use the designs differ fairly markedly.

Some of the methods, such as the Industrial Analog and the NOL methods, incorporate considerations of systems designs only implicitly. Others require a very explicit enumeration of the prospective weapon systems along with fairly specific designs.

The Industrial Analog method proposed to consider product complexities and lifetime in its synthesis of factors for determining the distribution of the Exploratory Development effort. However, much of the information on commercial and Defense product complexity and lifetimes is necessarily a transformation of ordinal human judgments to cardinal scaling. Little has been reported in the Industrial Analog material on studies of the complexity of the products in the technical fields. Moreover, regarding product lifetimes, major questions arise over product definition and whether modifications merely extend the lives of some products or whether the modifications result in new products.

The NOL method relies upon only a general functional analysis of weapon systems that could fulfill the operational requirements. These are incorporated into the Exploratory Development goals.

In TORQUE, members of the Interdisciplinary Team design weapon systems to fulfill the various operational requirements. In devising the weapon systems, the systems analysts are not compelled by the TORQUE procedure to compare the existing force structure, possible changes in tactics, possible modifications to the existing force structure and level, and potential new forces. Moreover, the TORQUE analytical framework does not evaluate these options in terms of operational requirement performance and full costs. Consequently, it leaves the uneasy feeling that these factors could well be ignored or that they have not been given reproducible and verifiable scrutiny.

Just as variations in the performance of an operational requirement are not recognized as separate events in the assignment of utility values, the different performance levels of the various systems employed in a requirement are not recognized. Each system applied to a given operational requirement is given full credit for the requirement's fulfillment. Undoubtedly, all systems that can be devised for a particular requirement will not perform in the same manner. By forcing all systems into this performance structure, TORQUE may be denying the technology and weapons managers the very real flexibility of being able to trade off some performance (and possibly some time to IOC) for costs.

Moreover, once the weapon systems are devised and introduced into the TORQUE framework, they are not treated as alternative means of supporting particular operational requirements. It is as though each requirement is insatiable, the deployment of any additional weapon system in a particular requirement's arsenal adding as much to its achievement as if the weapon were the first and only one in that arsenal.

The formulators of the FDL method have tried to get around some of these objections to the treatment of weapon systems in TORQUE. Analysts assign values to the various weapon systems according to the contributions they make to the different operational requirements. However, the analysts continue to treat the weapon systems as though they are perfectly independent of each other in contributing to operational requirements. Such independence is highly unlikely. There is no demonstration that various combinations of weapon systems should have weights equal to the sum of the separate weapons in those combinations. Moreover, there is no inherent limit upon the number of weapon systems that might be applied to any single operational requirement.

In the strict construction of the CAL method, the military "essentiality" of the QMDO is the basis for the measure of value used in the objective. This measure is replete with problems similar to those that affect value measures of the TORQUE and NOL methods. Although the method formulation might be appropriately modified and satisfactory value measures estimated for the QMDOs, the form reviewed treats the QMDOs as though they are independent of one another.

Further, each materiel concept in the CAL method is a necessary condition of the fulfillment of the QMDO for which it is a component. The materiel concept itself consists of a set of critical performance parameters. Such a formulation appears to be undesirably rigid. Trade-offs among performance parameters to maintain the intended effectiveness of the final weapon system configuration should be possible within any one materiel concept. Similarly, trade-offs among the performance characteristics of the different subsystems should be possible while preserving the final system effectiveness. Explicit formulation of these dimensions of variation would add significantly to the options available to management and probably lead to a better assessment of the overall probabilities of success of a program. Such a formulation should also provide avenues for planning lower cost programs that would achieve given military objectives.

Systems (and other types of follow-on contracts) play a pivotal role in the Hercules method. The marketing personnel calculate potential sales and profits that Exploratory Development might generate on the basis of the systems incorporating the projected technological advance.

In the Army Missile Plan, weapon systems are enumerated explicitly as the means for fulfilling operational requirements. The identification of the weapon systems is preserved and the connection of any single weapon system to a specific operational requirement remains visible throughout the subsequent planning steps.

c. Conclusions. Except in a commercial application, such as the Hercules method, or in an application of modest scope, such as the Army Missile Plan, weapon systems concepts do not appear to be treated adequately in the reviewed quantitative methods. Measures of the value of weapon systems (with regard to the achievement of operational objectives) ignore (1) the possibility that operational requirements may be fulfilled in different ways and to varying extents, (2) the possible interactions among systems when used in combination, (3) the substitutability of proposed weapon systems for fulfilling an operational requirement, and (4) the performance of proposed systems relative to possible variations in current force mixes and levels.

4. Technologies

a. Discussion. In quantitative methods that are used to plan Exploratory Development programs supporting weapon system development, the factor generally considered, once prospective systems are specified, is the technological composition of the systems. The technological composition breaks down the system design into the existing or projected engineering characteristics that the weapon system must contain if it is to perform in the way desired.

Functional relationships involving this factor trace the substitutions that might be made among technologies and possibly among some component operating characteristics across a number of system designs having the same overall performance qualities. These relationships also demonstrate how technologies may complement one another; that is, how some technologies must be used in combination in particular weapons systems to fulfill particular performance qualities.

Such relationships should facilitate tracing changes in the performance of a weapon system that take place as changes are made in the parameters of the component technologies.

Two levels of analysis must be performed within individual systems to determine the contributions of the subsystems and the component technologies. The first and higher level is that which must be performed within the system to compare major subsystems, e.g., to determine the importance of the guidance of a ballistic missile as opposed to the propulsion system. Such analyses would normally be performed by or under the cognizance of the Systems Command.

The second type of analysis is performed within a particular subsystem to identify the impact of various technologies. These would normally be prepared or sponsored by the Service laboratories. During the field survey, examples of good work of this type were identified, but they did not appear to be widespread. In rocket propulsion the Navy cited detailed studies such as those performed by the Naval Warfare Center on Advanced Tactical Stand-off ASM Systems which permitted the establishment of values for jinking, thrust modulation, and ramjet angle of attack sensitivity. The Army MICOM Propulsion Laboratory cited the SHORAD study in which the sensitivity factors of 18 items were determined (smokeless characteristics, diameter, weight, hot atmosphere effect, etc.). Analyses to evaluate more qualitative factors such as propellant storage characteristics are few and difficult to perform.

Estimates were made by the Service Propulsion Laboratories of the proportion of manpower devoted to studies of the second level mentioned above, i.e., analysis within subsystems. For the Army, Navy, and Air Force the percentages were 5, 2, and 3, respectively.

b. Technologies in the Reviewed Quantitative Methods. Some of the methods reviewed do not derive their proposed technological effort from fairly concrete future weapon systems. The Industrial Analog method, for example, proposes to relate current military Exploratory Development effort in a technology to the company-financed effort on the same technology in American industry. Also, the NOL method does not require fairly specific weapon system concepts to derive a desired technological effort.

One disquieting feature of the Industrial Analog is that its functional relationships describe historical conditions, and do not directly measure or project a connection between current R&D effort and currently demanded technological developments. Consequently, the allocation system contains a bias favoring continued work in the pattern of technical fields that supplied inputs to the weapon systems in the existing or recent past defense force structure. The effect that changes in the projected threat might have on the more basic categories of the research and development program under the Industrial Analog planning procedure is not clear.

In the NOL method, the analysts resort to the Exploratory Development goals to describe the work that must be done at the Exploratory Development level to satisfy operational requirements of future weapons and support systems, but these are not specific designs. Subsequently, each technology is assigned a "utility" index based upon the relevance of that technology to the EDG. However, the particular linkages of the technologies to the EDGs appear to ignore the substitutions that might be possible among the technologies and the complementarities that exist among them with regard to the EDG. Moreover, there does not appear to be any strict account taken of the level of the pacing parameter of the technology that would be needed to fulfill any single EDG.

The other methods derive the technologies to be included in the Exploratory Development program more directly from specific weapon system designs.

In TORQUE, for example, the profile of technology objectives that makes up any weapon system is expressed through the "criticality" value that the I.D. team assigns each technology objective with regard to each weapon system. These criticalities are largely subjective factors that confound at least three separable features: (1) the extent to which subsystems or technology objectives can be substituted for each other while maintaining equal effectiveness in a particular weapon system, (2) the cost implications of using specific technology objectives in a particular weapon system, and (3) the variations in the performance characteristics of a weapon system that might result from the use of some technology objectives.

These features should not be mixed up in this way; the first is a technological input trade-off measure, the second is an economic measure, and the third is a measure of the output quality trade-offs. In other words, the criticalities mix "apples and oranges" without any correspondence to the real counterparts of the relevant measures and trade-offs that are involved.

Moreover, as the criticality measures are used, they do not modify the effectiveness or weight attributed to a weapon system if some, but not all, of the component technology objectives are included in the Exploratory Development program.

None of the functional relationships in the TORQUE analytical framework incorporate explicitly any measure of the extent to which one technology objective may be substituted for another. Therefore, the method does not consider the particular technology objectives that can be substituted for one another to be <u>alternatives</u> for completing a weapon system or OCO. In fact, if more than one technology objective could fulfill a particular function but <u>only one must be developed</u>, the current structure of TORQUE would make all appear to be equally "critical."

Complementary technology objectives are those that are related to one another <u>and</u> mutually supportive in a particular weapon system. The current TORQUE framework does not include functional relationships that incorporate such complementarities into the considerations that must be taken into account.

Despite the intricate synthesis of information in the method, each technology objective is treated as an independent effort in TORQUE. Consequently, the method does not treat as alternatives those technology objectives that are substitutes for one another. Nor does it treat as complements those technology objectives that mutually support each other in particular weapon system configurations. In the current form of the "utility function," pursuit of a particular technology objective does not diminish the utility contribution of a substitute that could be added to the program without deletion of the first. Also, the utility function does not recognize that once a particular technology objective is chosen, its complements become "more important."

Within the relationships of the method, therefore, it is quite possible to choose a set of redundant technology objectives and, at the same time, a patchwork of technology objectives that would not make up a single viable weapon system.

These observations apply equally to the applicability factor employed in the FDL method.

On the other hand, the CAL method does, to some extent, take into account the possible substitutions and complementary relationships among technical objectives. This is accomplished through the substitutions that can be made among the alternative technical approaches to a particular materiel concept and the strong complementary relationships among the materiel concepts of a given QMDO. However, the CAL method does not extract the common technical goals that might be involved in several QMDOs. Each technical accomplishment contained in a QMDO is treated as though it is a component of only the one QMDO; commonality of technical work across technical approaches, materiel concepts, or QMDOs is ignored. This is a rather serious shortcoming since any commonality of technology objectives across the components of the planning structure would mean that the model is double counting costs, resources, and "tasks" that would be involved in an Exploratory Development program for a given profile of QMDOs.

In the Hercules method, work in the technologies is coupled precisely to specific projects and their products. The end-product orientation is not broken down in a subsequent procedure for evaluating each technology. Consequently, the extent of the work on any particular technology has a clearly defined impact on the expected payoff of a project. This provides ready surveillance of whether development is planned in all the pertinent technologies supporting a project. As a result, however, the method treats a technology either as a strict requirement of a project or as a perfect substitute for another technology in the project. As argued already this is a much too simplistic description of the trade-offs that should be possible. It does not make provision for the intermediate case, possibly more prevalent, in which the extent of development in one technology may be substituted to some degree for development in another technology, while both must be incorporated to some extent in the project.

As part of the Army Missile Plan, technical laboratory personnel enumerate the technological composition of the different systems without analysis of any possible trade-offs or other relationships among the technologies. Explicit couplings between systems and technologies are emphasized without pretense to more refined investigation of the results that might be expected from variations in the technological effort.

c. Conclusions. Except for the rather rudimentary step incorporated into the CAL method, little has been done in the reviewed methods to give adequate treatment to the possible substitution and complementary relationships of the various technologies composing the different weapon systems. In some of the methods, particular technologies are related to the system by some measure of criticality. Presumably technologies which are more critical are more important to the system. It is not made clear how this criticality is measured; further study of this matter is in order. The most likely specification for criticality would seem to be: potential advances in this technology would improve in system effectiveness more than the potential advances in other technologies. Further, the achievement of the stated level of advance for this technology is more important to the system than other technologies in that failure to meet the goals produces a greater loss in the effectiveness of the system.

In no case has a system postulated for a quantitative method been introduced with more than a single level of a subsystem quality. In the preliminary system analysis, comparisons should have been made among systems using alternative levels of the technology in question and a proper decision made on the utilization of the technology level specified. In fact, this is seldom done; the analysis is much less rigorous and based upon many previous small studies by the system designer.

Without more intensive analysis, the simplistic enumeration of the technological composition of different weapon systems, such as used in the Army Missile Plan, remains attractive. When cross-classified, a simple enumeration would at least make visible the technologies used in each weapon and all the proposed weapons incorporating a particular technology. In turn, this visibility could help the program planners understand better the impacts of their decisions on the effort to be expended on a particular technology.

5. Development Tasks

a. Discussion. For budget allocation purposes, the development task is the basic unit of effort that the analyst considers in planning work to advance a particular area of technology. A task is fairly specific in terms of the technological goals it attempts to achieve and the procedure it follows. As a factor that should be considered in a quantitative method for allocating the development budget, a task has two interesting aspects. One of these aspects is the pattern of developmental inputs that is used in the task. The other aspect is the position of the particular task as a component of a broader development effort directed at more complex technological accomplishments.

In the first of these aspects, the task is broken down into descriptions of how different patterns of development inputs may be related to steps in the advance of the technology. These relationships merge organizational and behavioral factors to derive alternative combinations of development personnel, materials, equipment, facilities and other inputs that might be used to advance the knowledge about and application of a technology. On the basis of such relationships, management can better understand how the inputs can substitute for each other and how they may complement each other in a development effort.

The second aspect sets the limits of the development context within which the particular task is performed and includes the framework within which the analyst can formulate relationships among the tasks to spell out alternative development strategies. In this aspect, the analyst is concerned with the sequencing of the various development tasks, the extent to which their results are interdependent, and consequently the coordination required among them.

The results of some development tasks may be completely independent of the results of others within the particular context. Such tasks can be performed either in parallel or in sequence, depending upon other considerations. On the other hand, the results of some other tasks might be highly interdependent in a number of ways. First, the overall development goal may require fairly tight combination of the outputs of the tasks. Second, the results of some tasks might be necessary inputs to other tasks. Third, some tasks may cover substitutable technological goals so that proceeding with a particular group of them may depend upon whether another group succeeds in achieving its goal. Analysis of the extent to which such tasks can be carried out sequentially or in parallel provides information describing, among other things, the development strategies that will result from different allocations of resources among the tasks.

b. Development Tasks in the Reviewed Quantitative Methods. With the exception of the Industrial Analog method, all of the quantitative methods reviewed break down the work that is to be done in each technology into a set of development tasks. The Industrial Analog attempts to determine the level of effort that should be devoted to a particular technology without specifying precise technical goals for separable units of work.

Among the other methods, the treatment of the development task as an element in Exploratory Development planning is highly diverse. The formulators of the methods not only resort more or less explicitly to tasks as the basic unit of effort, they also analyze the composition of the tasks' resource requirements in varying detail and spell out the interdependencies among tasks only to a modest extent.

In the NOL method, tasks are not included explicitly as planning factors, but some concept of them must be behind the functional relationships that describe the different levels of the technical pacing parameter that can be achieved with different efforts.

Other methods, such as TORQUE, FDL, CAL, Hercules, and the Army Missile Plan, do set out specific technical goals that each separable development task would attempt to fulfill. In some cases, like TORQUE, these tasks are also sequenced if they are considered to fit together, either side by side or end on end, in fulfilling somewhat higher and more complex technical goals.

However, the methods do not generally analyze explicitly the resource composition of the tasks or alternative patterns of resources in a specific task (or alternative tasks) that might achieve the same basic technical goal.

The FDL and CAL methods are exceptions. The FDL efforts on these matters are not extensive, however. The FDL method records only the in-house and contract engineering manpower composition of each task but does so in a way that permits these two inputs to substitute for or complement each other in a variety of patterns.

In the CAL method, provision is made for explicit treatment of the alternative patterns of inputs that might be used in tasks that are directly interchangeable for each other. The Army Materiel Command R&D Field Establishments and other resources make up the inputs that are accounted for in this way.

Among the methods reviewed, the CAL method is practically unique in setting out explicitly alternative sets of tasks that might be followed to fulfill a particular materiel concept. However, this approach only partially opens the question of choosing a development strategy. More than one set of tasks (technical approaches) can be adopted to ensure the success of the materiel concept. However, the method treats those sets as though they are executed in parallel. It does not make provision for following the different sets of tasks sequentially.

c. Conclusions. In general, the methods reviewed treat somewhat cursorily composition, context, and interrelationships of the development tasks into which they break up their Exploratory Development programs. Possibly, this results from difficulty with deriving precisely the technical goals that should be fulfilled from consideration of general, not specific, weapon system concepts. If this difficulty characterizes planning an Exploratory Development program and allocating the budget within that program, then some very basic conditions of the problem would appear to be fairly inconsistent with the application of highly precise quantitative methods to the allocation of the budget. On the other hand, inadequate treatment of alternative tasks that could fulfill specific technical goals and the wide range of relationships that can exist among different tasks also appear to be inconsistent with the use of precise budget allocation methods.

Unless alternative tasks and the relationships among tasks can be treated more completely and precisely, simpler methods for deriving and recording the development tasks of an Exploratory Development program are probably more desirable. For example, in the Army Missile Plan, the technical laboratories prepare a plan of tasks to achieve the technical advances required for the designs of the proposed weapons. The linkage of the tasks to the weapons is explicit and remains so throughout the subsequent steps of the Exploratory Development program planning process.

6. Costs

a. Discussion. The development task is the administrative planning unit for programming the specific application of development resources (such as manpower, material, and facilities). Therefore, it provides the background for estimating the costs that will be incurred in the development process. The estimated costs of a development program should measure the total expenditures management must make to obtain the resources needed for the execution of the program.

Three aspects of development costs are interesting for purposes of allocating the development budget. One of these aspects is the level of detail at which the costs are taken into account. A second aspect is the scope of the costs that should be taken into account. The third aspect is when the costs must be incurred to carry out the planned operations of the tasks.

Depending upon the level of detail desired in the accounting, the tally can be done in terms of general classes of resources or broken down into finer, more specific inputs. Among the general classes of resources, the analyst might include materials, operating inputs (such as labor and services), and facilities. Even with such a broad breakdown, explicit account should be taken of new investment requirements.

With finer detail, the analyst could focus on the specific capabilities of the different groups of research-engineering personnel and the applications of specialized equipment.

Regardless of the level of detail desired, the scope of the costs should include all expenditures for all resources employed in the development task. This may not be a simple and straightforward accounting exercise. Depending upon the budgeting techniques followed, some resources actually employed in the development process may be financed from other programs. For example, compensation for military personnel in development activities is not included in the appropriation accounts for military RDT&E. Expenditures that are directly related to the level of the development effort but made through other appropriations should be included within the scope of the total development costs, possibly treated as transfers.

Moreover, some real costs are frequently ignored completely in Government accounting techniques. For example, the user and interest costs that should be associated with the employment of such resources as land are frequently overlooked. If a particular Department or the Government owns the land, it generally does not impute such costs to its current operations since it does not make corresponding expenditures even though those resources could command compensation from employment elsewhere.

Another important consideration is the timing of the expenditures made to obtain the resources employed over the life of the development task. Recording the total costs and when they will be expended gives the manager the opportunity to evaluate the impacts of different time patterns of expenditure, possibly for budgeting purposes, and to have all the costs over the life of the task visible at one time. The latter should help to prevent wedging in high-cost development tasks through the illusion of low first-year costs. Keeping track of when the expenditures must be made also helps to determine the relevant scope of costs that should be considered. Expenditures actually made before the inception of the investment activities and operations of a particular task are not pertinent to the measure of costs that must be incurred for its execution. These expenditures have already been made, no further Treasury disbursements must be made to permit use of the associated inputs, and those inputs have no current alternative application.

b. Costs in the Reviewed Quantitative Methods. With the exception of the Industrial Analog method, all of the methods reviewed tally costs and resource requirements as a part of planning the component tasks of the development program. The Industrial Analog tries to compute the expenditures that should be made at a more aggregative level covering a broad technological area.

Most of the methods provide for estimating the costs of the tasks in the broadest aggregates, usually only the total costs that will be incurred in the execution of the task. The CAL method, however, does provide for recording the expenditures made on the various resources employed in the different tasks. Of course, the main virtues of estimating task costs in some detail are the explicitness the detail requires in the calculations and the possibilities for verification contained in the detailed records.

None of the methods reviewed describe in any detail the specific costs that should be tallied for consideration in the budget allocation process. This probably means that all of them let the analyst making the specific application decide what resource costs should be included. Or it might mean that the formulators were not aware of or concerned with setting the limits on the scope of the costs that are relevant for determining the composition of an Exploratory Development program.

The treatment of the timing of the expenditures that must be made for each development task is quite diverse across the methods reviewed, ranging from ignoring any costs that would be expended in any time beyond the current budget period to attempting an accounting of the total costs required over the task life. Although methods such as NOL, FDL, and CAL make provisions for different levels of expenditures, they appear to pay little if any attention to the costs that must be incurred during the life of the task beyond the specific budget period of immediate interest. The Hercules method attempts to consider the total costs that will be expended and the pattern of those expenditures for each project eligible for funding. In both TORQUE and the Army Missile Plan, the technical personnel who devise the development tasks that must be performed also estimate the pattern of the total costs to be expended over the lives of the individual tasks. The Missile Plan carries the time pattern of expenditures through its subsequent steps but pays most attention to the current year's budget and the corresponding expenditures in each task. TORQUE does try to combine considerations for both the expenditures to be made on the development task in the current budget year and the total costs to be expended upon the task over the remainder of its duration.

Because the cost concepts employed in the Industrial Analog method exemplify problems of detail, scope and timing, they warrant more detailed attention. The Industrial Analog method proposes to use as an indicator of the desired budget allocation to a technical area of military exploratory development the ratio of company-funded R&D expenditures to net industry sales.

By taking into account only the company-funded R&D expenditures by American industry, the measure ignores the substantial amount of research and development work that is supported by the Federal Government in these industries. The incidence of this support is by no means uniform as shown in Table 5.

Federal and company-funded expenditures on R&D within an industry are complementary, both contributing increased information about the technical field of study. Inasmuch as the companies performing the research and development generally can make commercial applications of the information generated by either funding source, Federal funding may be a significant contributor to their commercial success. If this is so, an Industrial Analog for Defense R&D based only upon company-funded R&D expenditures could substantially undercount the inputs that have been <u>necessary</u> for realized success.

Of course, counting the Federally funded industry R&D effort only leads to a further problem. If the Federal funds were included in the ratio and the ratio were an important component of the Defense allocation method, Defense R&D funding would not be independent of itself. In other words, the allocation process would be a circular one, turning back into itself, and ultimately self-confirming.

R&D funding data reported on a company basis must be used with care, especially if the company data are to be used to measure the R&D effort expended in the different product categories. For some reporting purposes, companies are classified in an industry according to their primary product, any single company being in only one industry at any one time. Insofar as companies have substantial interests in secondary products, counting all of their R&D funding as applying to

TABLE 5. FUNDS FOR R&D PERFORMANCE, BY INDUSTRY, 1965

Industry	Total	Company Funds	Federal Funds	Federal Funds as Percent of total R&D Funds
	(Millions of Dollars)			
Total	$14,197	$6,438	$7,759	55
Food and kindred products	150	148	1	1
Textiles and apparel	34	(b)	(a)	(a)
Lumber, wood products, and furniture	13	(b)	(a)	(a)
Paper and allied products	76	76	--	--
Chemicals and allied products	1,377	1,187	190	14
Industrial chemicals	928	781	147	16
Drugs and medicines	268	(b)	(a)	(a)
Other chemicals	181	(b)	(a)	(a)
Petroleum refining and extraction	435	366	69	16
Rubber products	166	141	25	15
Stone, clay and glass products	119	115	4	3
Primary metals	216	208	8	4
Primary ferrous products	131	130	1	1
Nonferrous and other metal products	85	79	7	8
Fabricated metal products	145	129	17	11
Machinery	1,129	870	258	23
Electrical equipment and communications	3,167	1,189	1,978	62
Communications equipment and electronic components	1,912	659	1,253	66
Other electrical equipment	1,255	530	725	58
Motor vehicles and other transportation equipment	1,238	913	326	26
Aircraft and missiles	5,120	620	4,500	88
Professional and scientific instruments	387	261	125	32
Scientific and mechanical measuring instruments	76	58	18	24
Optical, surgical, photographic and other instruments	311	203	107	35
Other manufacturing industries	67	66	1	2
Nonmanufacturing industries	359	103	255	71

Source: Ref. 20.

[a]Not separately available but included in total.

[b]Less than $0.5 million.

the products of the industry in which they are classified may be misleading for determining the distribution of R&D effort among technical fields or products. The data in Table 6 illustrate this problem. For example, of a $3.0 billion total, the electrical equipment and communications industry spent approximately $0.73 billion on applied research and development of atomic energy devices and guided missiles and spacecraft.

Three sources have been identified for the interindustry differences in the ratios of company-funded R&D expenditures to net sales (Ref. 21, pp. 59, 61). First, the demand for the increased performance of newly developed products is more or less intense in the various industries. Second, the cost or ease of generating significant new products is different by industry. Third, the amount of R&D performed in an industry tends to vary with the size distribution of the companies making up the industry, industries with predominantly very small companies spending relatively less than those industries composed mainly of larger companies.

While the demand and cost conditions of the first two sources of the interindustry differences are quite relevant and desirable guides for directing company-funded R&D effort, the appropriateness of the first for determining Defense R&D remains questionable. The demand for military goods may well be a component of the demand for the higher performance products from an industry, but the total demand for the higher performance products is also affected substantially by private sector and other Government preferences. That the total demand should correspond in some way to the demand for Defense performance improvements is a strong condition that would hold only accidentally.

The third source of the interindustry differences, the company-size distribution of the industries, is totally irrelevant for establishing Defense R&D priorities. In fact, this source could well generate undesirable results. In technical fields for which the principal industry is composed primarily of very small firms, the ratio will be relatively lower, indicating less DoD R&D funding than might be supported by other economic criteria, especially if the R&D benefits are dispersed. On the other hand, in technical fields for which the principal industry is composed of large firms, the ratio will be relatively higher. This could result in a higher level of DoD R&D funding for those fields than would serve defense efficiently, especially if the company-funded R&D is essentially dissipated on product differentiation to increase or maintain company market power.

Moreover, the ratio of company-funded R&D expenditures to net sales is an after-the-fact <u>description</u> of industry behavior, not a <u>prescription</u> of how industry should or is going to act. Even if industry had some infallible technique for determining its R&D budget size and allocation that was also appropriate for Defense, the ratio description of past behavior would give direction that could lag substantially behind the "desired" path.

Mansfield's investigations (Ref. 21, pp. 62-63) indicate that, in the short run, companies tend to maintain a fairly constant ratio of R&D expenditures to sales. However, given a longer time to adjust, companies change their <u>desired</u> ratio. The desired ratio generally increases with (1) increases in the forecasted profitability of R&D products, (2) "bandwagon effects" created by increases in R&D in related segments of industry, (3) decreases in the projected profitabilities of alternative uses of available funds, and (4) the tendency to maintain an absolute level of effort in the face of declining sales. A company may decrease the ratio as sales expand quickly in order to avoid the costs of rapid R&D expansion by building up to a desired level over a period of years. The speed with which a company adjusts its actual ratio to the desired ratio appears to be influenced by (1) the difference between the desired ratio and the previous year's ratio and (2) the ratio of the previous year's R&D expenditures to <u>profits</u>.

c. <u>Conclusions</u>. The level of detail at which the costs of executing Exploratory Development tasks are tallied is not crucial to the

TABLE 6. FUNDS FOR APPLIED RESEARCH AND DEVELOPMENT PERFORMANCE, BY INDUSTRY AND PRODUCT FIELD, 1965

(Millions of dollars)

Industry	Total	Product field and SIC code [a]							Product field and SIC code—Continued											
		Atomic energy devices	Ordnance, except guided missiles	Guided missiles and spacecraft	Food and kindred products	Chemicals, except drugs and medicines	Drugs and medicines	Petroleum refining and extraction	Rubber products	Stone, clay, and glass products	Primary metals	Fabricated metal products	Machinery	Electrical equipment, except communications	Communication equipment and electronic components	Motor vehicles and other transportation equipment	Aircraft and parts	Professional and scientific instruments	Other product fields, not elsewhere classified
	—	—	(19, except 192)	(192)	(20)	(28, except 283)	(283)	(29, 13)	(30)	(32)	(33)	(34)	(35)	(36, except 365–67)	(365–67)	(37, except 372)	(372)	(38)	—
Total	$13, 590	$665	$103	$3, 765	$224	$1, 022	$263	$203	$116	$91	$178	$158	$1, 121	$323	$2, 131	$724	$1, 387	$407	$709
Food and kindred products	139	-------	-------	-------	(b)	(b)	(b)	-------	-------	(b)	(b)	(b)	(b)	(b)	(b)	-------	-------	(b)	(b)
Textiles and apparel	32	-------	-------	-------	(b)	5	(c)	(b)	1	(b)	-------	(b)	1	-------	-------	-------	-------	(b)	24
Lumber, wood products, and furniture	(b)	-------	-------	-------	-------	(b)	-------	-------	-------	(b)	-------	(b)	(b)	-------	(b)	(b)	(b)	(b)	(b)
Paper and allied products	74	-------	-------	-------	(b)	6	-------	-------	(c)	-------	(b)	(c)	7	(b)	1	-------	-------	(c)	60
Chemicals and allied products	1, 205	86	7	3	22	708	233	10	8	6	14	6	22	(b)	3	(b)	35	(b)	30
Industrial chemicals	811	86	7	3	4	576	38	10	5	4	14	4	19	(b)	3	(b)	(b)	2	26
Drugs and medicines	228	-------	-------	-------	5	36	180	-------	1	(b)	-------	(b)	3	-------	-------	-------	-------	(b)	1
Other chemicals	167	-------	-------	-------	13	96	14	(c)	2	(b)	-------	(b)	(c)	(b)	(c)	-------	(b)	(b)	4
Petroleum refining and extraction	382	(c)	(b)	40	(c)	100	1	185	1	1	4	(b)	2	(b)	(b)	(b)	(b)	2	(b)
Rubber products	157	(b)	(b)	(b)	(b)	(b)	(b)	-------	(b)	(b)	(b)	(b)	(b)	-------	(b)	(b)	(b)	(b)	(b)
Stone, clay, and glass products	112	(b)	(b)	(b)	-------	(b)	-------	(b)	(b)	(b)	(b)	(b)	(b)	(b)	(b)	(b)	(b)	(b)	(b)
Primary metals	203	2	1	1	(b)	15	-------	1	1	(b)	128	19	10	5	3	4	2	(b)	10
Primary ferrous products	121	(b)	(b)	(b)	(b)	(b)	-------	-------	(b)	(b)	(b)	(b)	(b)	(b)	(b)	(b)	(b)	(b)	(b)
Nonferrous and other metal products	83	(b)	(b)	(b)	(b)	6	-------	1	(c)	(b)	38	9	6	4	3	(b)	(b)	(b)	(b)
Fabricated metal products	141	(b)	(b)	(b)	(b)	(b)	(b)	(b)	(b)	(b)	(b)	(b)	(b)	(b)	(b)	(b)	(b)	(b)	(b)
Machinery	1, 103	2	6	59	1	7	(c)	1	1	1	3	22	706	15	164	31	17	6	61
Electrical equipment and communication	3, 020	373	28	360	(b)	20	(b)	(b)	2	5	7	18	175	212	1, 275	14	212	148	74
Communication equipment and electronic components	1, 791	(b)	16	149	(b)	1	-------	-------	(b)	1	2	6	106	19	1, 034	10	27	107	43
Other electrical equipment	1, 229	(b)	12	210	(b)	18	(b)	(b)	(b)	3	5	12	70	193	241	4	185	41	31
Motor vehicles and other transportation equipment	1, 201	(b)	31	80	(b)	8	-------	(b)	6	(b)	9	23	94	53	178	651	58	3	3
Aircraft and missiles	5, 052	121	12	3, 131	(b)	30	-------	(b)	8	1	4	7	33	5	438	9	991	6	256
Professional and scientific instruments	(b)	(b)	(b)	(b)	(b)	(b)	(b)	-------	(b)	(b)	(b)	(b)	(b)	(b)	(b)	(b)	(b)	(b)	(b)
Scientific and mechanical measuring instruments	73	3	2	3	-------	(c)	(b)	-------	(b)	(b)	(c)	6	5	8	9	2	3	24	7
Optical, surgical, photographic, and other instruments	(b)	(b)	(b)	(b)	(b)	(b)	(b)	-------	(b)	(b)	(b)	(b)	(b)	(b)	(b)	-------	-------	(b)	(b)
Other manufacturing industries	(b)	-------	(b)	-------	(b)	(b)	-------	-------	(b)	(b)	(b)	(b)	(b)	(b)	(b)	(b)	-------	(b)	(b)
Nonmanufacturing industries	330	(b)	(b)	(b)	(b)	(b)	(b)	(b)	(b)	(b)	(b)	(b)	(b)	(b)	(b)	(b)	(b)	(b)	(b)

[a] Ref. 22. [b] Not separately available but included in total. [c] Less than $0.5 million.

budget allocation procedure. Detail may force explicitness in the calculations and permit more ready verification of the cost estimates; however, it can be neutral in generating a desirable allocation of development funds.

However, determining the proper scope of the costs that should be taken into account and the timing of the incidence of those costs are extremely important considerations for establishing a desirable allocation of the development budget among technologies. Ignoring the question of the scope of the costs that should be included among the factors considered in a quantitative method is quite similar to acting like an ostrich. Without accounting for the proper scope of costs and the timing of their incidence, the Exploratory Development manager could well choose a set of development tasks that imposes substantially higher costs on the Defense community or the economy as a whole than would be necessary to accomplish the same technical goals. Costs incurred for the execution of the task but financed from another appropriation or in the future are nonetheless real and burdensome on the productive capacity of the economy.

The methods reviewed have adequately treated neither the scope of the costs nor their timing. None raise the question of, let alone analyze, the scope of the costs to be included among their considerations.

Because of an inordinate concern for the one-year budgeting procedure, most of the methods reviewed consider only the costs that would be incurred by a project or program in the next year. If it accomplishes anything, such an approach puts a heavy premium on getting very large projects in the door by starting them at very low levels of effort.

Concern for total project life costs does not require neglecting the budgetary procedure. In fact, a better picture of future budget needs can be produced using total costs and dating expenditures according to the time they will be made.

7. Timing

a. Discussion. The timing of the events in a development program and the amount of time that elapses in the course of those events are important factors that should be considered in planning an Exploratory Development program and allocating the program's budget. For the most part, these timing factors characterize some aspects of the factors already analyzed. Reference has been made to these aspects in several instances above. However, where timing could be separated from that discussion without giving misleading impressions, the analysis of timing was postponed.

Timing is a thread running thoughout the range of factors. When an operational requirement is fulfilled, when a weapon system is completed, when a crucial technology is advanced to a useful level, when development tasks are undertaken and completed, and when expenditures must be made to obtain the inputs necessary for a development task are all important features of the individual factors. In combination, these features require coordination and integration if the development program is to be successful and ultimately contribute to higher order Defense objectives.

For purposes of Exploratory Development program planning, the timing of the fulfillment of an operational requirement and the completion of a weapon system are principally external considerations derived from other Defense criteria. However, the timing of the advance of a technology and the timing of a development task fall, to a large extent, within the proper scope of Exploratory Development planning. The basic considerations are the time that is required to complete a development task and the timing of that development task relative to other tasks with which it might be interdependent. These determine the timing of any more complex technological advances.

Time-cost trade-offs arise when the time elapsed in the execution of a particular development task can be varied or when tasks with essentially the same technical objective have different time requirements. Time-performance trade-offs can also be made in a similar manner if tasks having somewhat different technical objectives and time requirements are essentially substitutable for each other.

The development strategy followed in any program consists, at least in the first instance, of determining the timing of the execution of the individual tasks within a group that is interdependent. A strategy of concurrency is followed when a number of interrelated tasks are undertaken at the same time. A sequential strategy is followed when the timing of the interrelated tasks is arranged so that only one is executed at a particular time with the execution of the others being dependent upon its success or failure.

Timing of the expenditures that must be made to obtain the resources employed in the development tasks has been discussed in some detail in Section IV-C-6.

Taking into account the timing aspects of all the other factors in a method for allocating the Exploratory Development budget is obviously important for management. It not only helps management to know when technological developments or weapon systems will be available, it also gives management the information that it can use to exercise whatever discretion it may have to influence the timing of individual tasks, sets of tasks, and expenditures. Management can apply its time preferences and discount rates to the time-phased technological advances and expenditures to compare alternative courses of action and choose among them.

b. Timing in the Reviewed Quantitative Methods. Among the methods reviewed, the Industrial Analog does not take into account any consideration of the timing of the development effort or the expenditures for the inputs employed. As was pointed out above, its lack of explicit treatment of this matter results in it proposing to relate current and future Defense expenditures on a technical area to past commercial expenditures in related fields.

Most of the other methods reviewed have two common characteristics in their treatment of timing. They generally approach the problem of allocating the Exploratory Development budget as though it extends through one time period, with funds and work to be chosen only for the next budget period. Also, the methods pay little attention to variations that are possible in the completion times of the different development tasks.

Generally, a fair amount of timing information is behind the treatment given the various factors in the different methods. Some of it is extensive and used quite explicitly to put the data on the factors in the form incorporated into the quantitative operations of the methods. In the NOL method, however, timing considerations are implicit, at best. It is principally concerned with the extent of the advance that can be made in the pacing parameters over the next budget year without explicit reference to any target times for a level of advance, weapons, or EDGs.

The Hercules method considers explicitly (1) the timing of the marketing of the product from the development project, (2) the time required to achieve the technical goals needed to complete the project, and (3) the modification of the project completion time that is possible by varying expenditures on component tasks. However, the method does not take into account the time preferences that management may have for the sales and profits of the project's product or for the expenditures that must be made to complete the project. Applying a discount factor to profits and expenditures could easily remedy this last shortcoming.

Because of the flexibility it has in the specification of different technical approaches that can be followed to a particular materiel concept, the CAL method can similarly consider the timing of the component development tasks and the satisfaction of each QMDO.

The TORQUE, FDL, and Army Missile Plan methods utilize detailed information on the target times of the weapon systems their development programs should support, the timing of the development tasks making up the programs, and the timing of the expenditures that must be made for alternative tasks. The Army Missile Plan carries this information along in the budget allocation process, being concerned primarily with the time at which the weapon system will be available and the tasks that should be performed in the next budget period. TORQUE and the FDL method use the timing data in more elaborate calculations for evaluating the level and timing of the development tasks that should be executed.

Both TORQUE and the FDL methods calculate factors that are used to set the value of each development task according to whether the timing of its successful completion will permit completion of the weapon system incorporating it by the weapon's target date. Besides the completion date of the task and the target dates of the weapon system, the pivotal concept used in this calculation is the timeliness function (Fig. 2).

> ...Two [target] dates are needed for each system/subsystem to reflect the time span during which initial deployment in operational units is desired for maximum overall effectiveness. The 'earliest date' needed is such that existing equipment, or equipment scheduled for procurement, is expected to still be satisfactory. The 'latest date' recognizes the uncertainty involved in establishing a precise initial deployment date. (Ref. 8, p. 7)

However, the manuals do not indicate the criteria that should be applied by the systems analysts to judge whether existing equipment or equipment scheduled for procurement remains "satisfactory."

The timeliness function used in TORQUE and the FDL method is based on the two valid premises that (1) development of a technology objective long before it is needed in a weapon system may be wasteful of current resources, foreclosing their use in projects with nearer term payoff, and (2) completion of a technology objective for the introduction of a weapon system is wasteful if its relative effectiveness has already deteriorated because of changing external conditions. Both premises are indicative of behavior that should be avoided. However, the particular timeliness function that has been devised is a rather rigid proscription of behavior, with possible mischievous consequences.

The judgment is arbitrary that development of a technology objective before its "need date" is absolutely wasteful (the TORQUE timeliness function dictates that a technology objective developed more than two years before its "earliest need date" is worth nothing). Waste of resources is better judged by whether they could be employed in developments with greater "utility." Of course, a unit of utility achieved sometime in the future is not preferred to a unit of utility achieved at present. However, the trade-off between present utility and future utility is far better evaluated through analytical procedures reflecting time preferences rather than arbitrary cut-offs of the planning time frame.

With the timeliness function, the rapid development of a technology objective supporting a very important system that is scheduled for procurement in the relatively distant future may receive no utility credit because of the arbitrary cut-off. A result may well be that TORQUE would divert funds to very "low priority" efforts because they are closer in time, contrary to Defense management's time preferences for the utility of the more remote but important system.

The timeliness function is similarly arbitrary in the way it describes and handles the declining relative effectiveness of a weapon system as the threat and newer weapon systems develop.

In general, explicit treatment in systems analysis of each prospective system's effectiveness relative to (1) the current forces; (2) changes in tactics, force structure, and force level; (3) other prospective systems; and (4) the evolution of the threat, would be far more desirable for tracing the value of that particular system over time. The timeliness function attempts to integrate all of these considerations into a single, rigid, and arbitrary expression, applicable to all systems regardless of the surrounding circumstances.

The estimates that must be made to implement explicit treatment may have large variances because of the uncertainties of future weapon system performance and the evolving threat. Their accuracy, however, could hardly be less than that of the timeliness function. On the other hand, the increased flexibility that should result from explicit and individual attention to weapon system effectiveness will ensure that important options are not excluded from consideration.

c. Conclusions. The timing of the execution of development tasks, the expenditures for resources employed in the tasks, and the achievement of technological advances cannot be ignored in determining the allocation of the development budget. These timing aspects are important considerations that must be taken into account if alternative development tasks having similar technical objectives but different time requirements can be selected and if the timing of the technological advance is at all significant to management.

Some of the methods reviewed call for a large amount of detailed information on the timing of tasks, expenditures, and technological advances. Unfortunately, none use these data in a way that would ensure the proper time distribution of the budget allocation. Most of the methods concentrate on the budget requirements for the next budget period without regard to the pattern of expenditures required thereafter. Those methods, such as TORQUE and FDL, that try to take account of the future pattern of budget requirements, do so by means of calculations that are rather arbitrary and without firm analytical bases.

Without a demonstration that the added complexity of calculations such as the timeliness function ensures a desirable time distribution of the budget, the complexity is probably best avoided. Unless the timing aspects of tasks, expenditures, and technological advances can be incorporated into the method with strong and verifiable normative underpinnings, simpler, yet visible, listings of these considerations would be more desirable.

8. Risk

a. Discussion. Risk is a measure of the extent to which the various aspects of the actual outcome of a development task can deviate from the results predicted for the task before its execution.

In some respects, a development task is much like a production process. A group of inputs is assembled and organized in a way to generate a product, in this case a technological advance. However, if any one characteristic distinguishes Exploratory Development from the general run of production activities, it is the difference in the risk that confronts the development manager. The development process is not a repetitive, single-product, manufacturing process in which experience with the pattern of inputs and products eventually cuts down the variance between predicted and actual quantities. Each development task is a new experiment with significantly different intended products and little comparative experience to draw upon to specify alternative "production processes." Consequently, the possible variance between predicted and actual results is relatively much greater in development.

In an Exploratory Development task, the actual resource requirements, actual timing of execution, actual elapsed time requirements, and the actual technological advance achieved can vary from the predictions made of these characteristics before the task is executed. These are jointly distributed characteristics, each of which can be controlled with varying degrees of precision but for which the control of any one is achieved at some loss in the control that can be exercised over the others. The variability in the actual outcomes of these characteristics in each development task carries through the broader development process, in a compounded way, into the ultimate configuration of the weapon systems developed and their fulfillment of operational requirements.

The risks that the development manager faces with regard to each of these characteristics and the relationships among them should, in some way, be taken into account in the allocation method if it is to represent at all adequately the real allocation problem. When the risks associated with individual characteristics and the relationships among them are considered, the trade-offs that can be made among the characteristics become visible so that they can be evaluated explicitly in the allocation of the budget. Consequently, to gain assurance of a satisfactory technological advance, development management may consciously choose to finance a development task that requires an acceptable time for completion but has greater expected costs and a greater possible adverse cost variance than other tasks with the same objective. Or management can also explicitly consider whether the assurance it may gain in achieving a particular technological advance by increasing the funding of its related task is worth the assurance that must be sacrificed in the achievement of the technological advance sought in another task whose funding must be decreased.

b. Risk in the Reviewed Quantitative Methods. Most of the methods that were reviewed do not take into account the risk involved in the many aspects of the development process. These methods set out the various factors as though the results of any projected course of action are known precisely beforehand. Their calculations use "point" estimates of the resources employed in the various development tasks, the technological advances generated by the tasks, and the timing of the execution of the tasks.

The FDL, CAL, Hercules, and Another Service methods do incorporate some considerations of the risks that are involved, but the approaches of these methods are quite dissimilar.

The FDL method primarily associates risk with whether the technological advance generated by a task will, in fact, fit into the weapon system for which it was undertaken. The method treats the advance generated by various levels of effort in the task and the timing of the advance as if they are known precisely but each known level of advance as if it fits the weapon with some probability. The task and advance are only complete once the latter fits the weapon for which it has been designed with a probability of 0.8. At best, this treatment only alludes to the risks that are involved in Exploratory Development tasks. Having chosen the 0.8 probability as the criterion of success, the method, in effect, has converted the problem to one based upon "point" estimates of the factors.

The CAL method, and similarly Another Service method, incorporates risk into its framework in terms of the probability of success of the individual development tasks constituting a particular technical approach to a materiel concept. This probability of success might be stated as: the probability that an advance at least as great as the advance needed for the technical approach will result from the planned expenditure on the task within the next budget period. All the tasks within a given technical approach must succeed in these terms for the technical approach to be successful, and at least one technical approach must be successful for the completion of the materiel concept. Finally, all materiel concepts within a QMDO must be completed successfully for the fulfillment of the QMDO. By this sequence of steps, each step consisting of a compounding of the risks involved in the more basic development taks, the CAL method attempts to evaluate the technical risks that characterize the development of a complex weapon system.

The Hercules method attempts to carry the consideration of risk somewhat further. It not only requires estimates of the technical risks involved; it also uses estimates of the marketing and profitability risks. Technical risks consist of engineering estimates of the probabilities that new research must be performed for the completion of the project and that the technical goals of the planned development tasks will be reached within the proposed time and funding patterns. The marketing organization's input to the method consists of estimates of the probabilities of different sales volumes and profit margins of the project's output when it is marketed.

c. Conclusions. The reviewed quantitative methods largely ignore the risks that are involved in the real, counterpart, exploratory development process. The only application of a fairly thorough representation of the risks involved in development is the Hercules method, a commercially oriented method for allocating a development budget. The CAL method does have a good framework for portraying the technical risks that are involved at different levels of the development process. However, its utility for allocating a military Exploratory Development budget would ultimately depend upon the quality of the information used in its application. No applications of the method were found, so final judgment must be postponed. The concept of risk introduced into the FDL method barely qualifies as a serious consideration of the matter. Moreover, the limited factors to which the risk concept applies do not give the manager any appreciation of the extent to which the actual outcomes of the development efforts funded can deviate from those outcomes predicted at the time the funding decisions are made.

Risk is not a simple factor to incorporate into quantitative methods for allocating a development budget. The underlying concepts are difficult to formulate, and the data necessary to make those concepts operational are difficult to obtain.

For the most part, it is impossible to obtain historical data depicting risk that apply directly to the actual factors involved in a current budget allocation problem; each new development task undertakes to discover something about relatively unknown phenomena. The data that are used are generally estimates of plausible distributions of the outcomes of prospective tasks. Often the personnel who would execute the tasks are also the estimators of the risks involved. While these personnel are probably the best informed to make such estimates, their involvement in the execution of the task does not always lend to their making estimates as objectively as possible.

The precise mathematical formulation and numerical representation of the risk involved in development have not been successfully treated in quantitative methods for allocating the Defense Exploratory Development budget. Explicit and precise incorporation of the risk factor into such methods appears to require more development work itself. Obviously, without consideration of the risk involved, a method cannot represent for management the range of trade-offs that is important to its budget allocation decisions. Until more precise treatment is possible, a simpler but systematic approach would be desirable. Such an approach might consist of making visible some evaluation of the chances that actual outcomes may differ from predicted outcomes for a few basic factors in the development process without attempting to compound these risks into the arithmetic of the allocation.

D. CONSTRAINTS

1. Discussion

In a quantitative method for allocating the Exploratory Development budget, constraints are the limitations that the analyst and manager apply to possible courses of action on the basis of considerations outside the narrow scope of Exploratory Development. They define more precisely the range of development activities that can be considered seriously by setting specific limits on the relationships among the various factors in the problem or by setting limits on some of the factors directly.

Obviously, in the present planning context, resolving the allocation of resources among the projects of the Exploratory Development program cannot depend upon complete systems analyses or solution of the total Defense resource allocation problem. Exploratory Development is performed much too early in the evolution of a new system for sufficient information to be available for a complete systems analysis. Formulation of the total Defense allocation problem in a rigorous planning method is not currently practical, if at all desirable. To be at all manageable, the allocation of resources within Exploratory Development must be treated as a subproblem, truncated in scope but structured consistently with the more general Defense allocation problem.

The analyst can use constraints to truncate the Exploratory Development problem properly and to set it up in such a way that it is consistent with the more general Defense allocation problem.

One type of constraint consists of restrictions on the progress that might be sought in any one technology or on the configurations of the weapon systems that will result from the development effort. Several kinds of reasons might give rise to such bounds. For example, external scientific information might indicate that it is not feasible to achieve some level of a critical parameter in the technology. If the information indicates that conditions change quite abruptly at this level, a restriction might be used to prevent expenditure of further effort in that direction.

Similar constraints might be placed on the technical configurations of weapons systems based on systems analyses that are done outside the Exploratory Development planning process. Some minimum level of a performance characteristic in a weapon system might be imposed on the allocation method as a result of intelligence estimates of enemy capabilities.

Another type of constraint that is commonly imposed on an allocation method is a limitation on the resources available. This may take various forms, including a restriction on the overall level of expenditures that may be made or specific restrictions on the availabilities of individual resources such as facilities, equipment, materials, and manpower. Although these are generally in terms of upper bounds, the condition might be reversed in some cases, requiring that a minimum amount of some resource be used. That latter situation can commonly arise as the mix of Exploratory Development work changes, giving rise to a changing pattern of demand for resources. However, other considerations may lead to a desire to stabilize the composition of the resources on hand or to maintain some minimum level of a certain capability.

Any limitations based on higher policy-level requirements can be imposed on the method to limit further the range of options that may be chosen for the Exploratory Development program. However, if these are properly formulated in the method, the analyst should be able to evaluate the costs that these constraints impose on the program in terms of higher funding requirements, foregone technological progress, or changed weapon design.

2. Constraints in the Reviewed Quantitative Methods

The use of constraints in the reviewed methods falls into three classes. First, some of the methods use no constraints in their characterization of the budget allocation problem. Second, some of the methods use only one constraint, the total budget that is available. Third, a few of the methods employ a number of constraints on a variety of aspects within the allocation problem.

The Industrial Analog and Army Missile Plan methods fall into the first type (use no constraints) but they are significantly different in their general formulation. Actually, the Army Missile Plan is less a budget allocation method than it is an information system for making visible the derivation of the technological developments that are necessary to support projected weapon systems. Relationships among the various factors appear to keep the development tasks that could be undertaken closely linked to the proposed systems. With a modest primary objective and close linkage between systems and tasks, additional constraints might be used to restrict the number of systems supported for any one operational requirement. However, this can also be done successfully by limiting the number of proposed weapon systems.

With its completely misdirected primary objective, the Industrial Analog would need a set of constraints that would, in effect, completely override the criteria of the objective to ensure an allocation of Exploratory Development funds supporting Defense technology needs.

The TORQUE, NOL, and Hercules methods follow the second approach, only constraining the allocation to use no more than the total budget available. The Hercules method has both a fairly well-defined primary objective (to maximize company profits) and a relatively precise value measure (profits). These might be expected to set clearly the limits on the development tasks that could be undertaken except possibly for adequate consideration of the specific skills and facilities available to the company. However, in an application of the method to plan one year's program, management found need to impose an impromptu constraint on the allocation generated by the method. In that particular year an extremely large contract appeared probable in the very field of rocket propulsion for which Hercules was well equipped. If the potential contract were incorporated in the Hercules allocation methodology without qualification, its immensity would have resulted in an allocation of essentially all resources toward the one contract. Feeling that this was not reasonable, the management exercised its discretion to limit the allocation to that particular project. Such a constraint undoubtedly signifies that some other factors were not incorporated into the method satisfactorily.

The TORQUE and NOL methods also only take into account the overall limitation on the budget that is available for Exploratory Development and ignore limitations that might exist on the availability of specific skills and facilities. In addition, both methods have rather nebulous, unverifiable primary objectives and value measures that do not have sufficient inherent properties to prevent the method's generating allocations with inconsistent and redundant tasks. These methods make no provisions for constraints that would prevent such negative features. Systems specifications in TORQUE characterize this problem.

As the procedure for implementing TORQUE is set out in the manuals and was followed in the experiment, the TORQUE method does not give assurance that it is consistent with the general Defense allocation problem. The principal connection of the Exploratory Development planning process to the overall Defense allocation problem is through the projected weapon systems that Exploratory Development is expected to support in its own program. Consequently, TORQUE's consistency with the larger problem depends upon the choice of the weapon systems used as the basis for determining the technology of objectives of Exploratory Developments. TORQUE basically has little or nothing to do with the procedure for choosing the set of prospective weapon systems that should guide the planning of technology development. But it also does not clearly incorporate those prospective major weapon systems that should be determined by the systems analysts, into the stream of that should be determined by the systems analysts, into the stream of data and assumptions used in its calculations.*

Besides limiting the total allocation to the budget available for Exploratory Development work, the FDL method does take into account the availability of some specific resources for this work. In published reports, the method considered restrictions on the amounts of in-house and contract engineering manpower that could be employed in the resulting tasks. This is an important consideration and, in principle, establishes that some specialized resources might limit the size or rate of expansion of the program. However, the FDL method has the same shortcoming as TORQUE and NOL regarding the specification of the systems that should be considered in the derivation of the development tasks.

In addition to a constraint on the total budget that can be allocated, the CAL method employs QMDO and resource constraint concepts. The QMDO constraint ensures that at least one technical approach to each materiel concept of a specific QMDO will be included in the final program if a QMDO constraint is stated for that particular QMDO. Unfortunately, the probability of success of the QMDO is not at all considered in this regard. Consequently, a very low-cost, low probability-of-sucess configuration of technical approaches might be retained in the program for a "necessary" QMDO.

The principal purpose of the resource constraint is to make sure that the funding of a particular field establishment does not fall below some predetermined level. The particular formulation of the resource constraints can lead to perverse results. A technical approach will not be eliminated from the program if its elimination will violate a resource constraint; that is, if its elimination would lead

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*Although the particular matter falls outside the scope of this study, recognizing that the determination of the weapon systems options is so important to technology development planning raises the further question of whether the current state of systems planning is sufficient to fulfill this function.

to less being expended at a field establishment than the minimum previously determined. This is, at best, a rather crude "make-work" provision that can only lead to higher development costs than necessary for prospective weapon systems. It can actually prevent distribution of the work among the field establishments on the basis of their absolute or comparative efficiencies in the technical areas. Consequently, the resource constraints prevent the field establishments, as a whole, from achieving the maximum possible "research and development output" under the given funding conditions.

Minimum levels of effort at the field establishments are set to satisfy objectives other than the development of the specific QMDOs being investigated at any one time. Both sets of objectives could be better served if they were not confounded through this particular formulation of the resource constraints.

3. Conclusions

Constraints are the means by which the method formulator can introduce considerations into the analysis of the allocation problem to make it correspond more closely to the real counterpart budgeting problem. They can also be used to fix limits on the range of factors that must be taken into account in the allocation problem. In this way, constraints truncate the scope of the problem to fit more closely the primary concerns of Exploratory Development by imposing on it outside policy and technical decisions.

The formulators of the methods reviewed did not exploit this analytical feature as effectively as might be desired. In most cases, it seems that the formulators were conservative in their recourse to these devices. Of course, the formulators pay a price in using constraints. First, constraints are often difficult to translate into an acceptable mathematical form and their numerical content is often difficult to estimate. Second, constraints generally add to the computational burden of solving the desired allocation of the budget.

However, even in the CAL method, where constraints are used fairly freely, the particular forms of the QMDO and resource constraints do not effect very well the external decisions dealing with QMDO completion and facilities funding.

E. DECISION ALGORITHM

1. Discussion

In the final step of a quantitative method, all the factors considered in the problem are combined with the objectives and constraints in a decision algorithm to determine the funding of each proposed development effort. This decision algorithm is basically a formal set of rules for calculating the level of funding. It uses the mathematical representations of the factors in a way that reflects the considerations management should make in forming its choices.

Algorithms used in allocation methods in general can be quite diverse in their mathematical complexity and rigor. Very simple rules of thumb applied consistently qualify as algorithms as much as the very complex mathematical techniques involved in combinatorial search routines, Lagrangian multiplier methods, and linear, nonlinear, and dynamic programming.

For the most part, the criteria of the usefulness of an algorithm consists of whether it treats the factors of the problem consistently, whether it combines the factors and represents their relationships in a way that reflects the real counterpart to the allocation problem, and whether the computational procedure is consistent with the primary objective of the allocation method. In a formal mathematical algorithm, the last of these criteria is generally demonstrated through a proof that the mathematical procedure converges to an allocation that best satisfies the primary objective. The first two criteria are satisfied if the mathematical expressions for the factors and their relationships are formulated properly and cover the proper range of considerations.

2. Decision Algorithms in the Reviewed Quantitative Methods

Even within the relatively small number of quantitative methods reviewed for this investigation, a wide range of decision algorithms is used. This range includes a simple listing of development tasks, linear programming, and combinatorial search routines.

The Army Missile Plan uses a simple listing of the proposed development tasks. The ordering of the tasks in the list depends upon (1) the initial operational capability date of the weapon system in which the results of the task would be used, (2) the ordinal importance of the weapon system revealed in Army planning documents, and (3) the indispensibility of the task results to the weapon system. Once the order of the tasks is established, the funds are allocated to each task in descending order on the list according to the resource requirements of each, until the total budget is exhausted.

The simplicity of this procedure is quite appealing. The task order and the steps in the allocation are visible and readily comprehensible. The obvious drawback is that it does not represent very well the full range of options that the management of Exploratory Development must take into consideration. Alternative development tasks with the same technological objective cannot be evaluated readily. Also the procedure does not take into account how some higher priority tasks might be stretched out at lower funding rates in order to permit the starting of tasks that have somewhat lower ordinal priorities.

Little objection can be raised with the mathematical procedures of the algorithms used by the NOL, FDL, and Hercules methods. The NOL method uses a Lagrangian multiplier type of algorithm, the FDL a linear programming algorithm, and the Hercules method a combinatorial search routine. In the NOL and FDL methods, as long as the mathematical formulations of the factors and the relationships among the factors have the proper forms, the algorithms lead to best solutions. Consequently, any objections to them must stem from how well these mathematical formulations represent the real counterpart conditions surrounding the factors. Most of the shortcomings in the treatment of the various factors in these methods have already been reviewed above. However, some observations on these methods deserve emphasis in the present context.

The Index of Advance, Fig. 3 above, plays a crucial role in the NOL method; the particular form of the curve assumed in the description is necessary if the algorithm is to apply properly. However, the field survey of this investigation indicated that other shapes of such value functions may describe better the real counterpart technological progress (cf. Fig. 9). If these other shapes are more appropriate, the NOL algorithm can no longer ensure that its allocation satisfies best the primary objective specified for the method.

In the FDL method, the weapon systems and technical goals devised are extremely important components of the functions that define the military value of each development task (Section III-D-5). Inspection of the form of this function indicates that the value of a task is dependent upon the number of weapon systems and technical goals it supports, as it should be. However, without some additional constraints, a well-chosen, and arbitrary, proliferation of the right weapon systems and technical goals can weight the recommended allocation incorrectly in favor of some tasks.

As is the case with any algorithm, the final test of the combinatorial search used in the Hercules method is the resulting allocation. In this regard, it might be reemphasized that management rejected the allocation generated in one application of the method when its solution indicated that practically all of the funds should be devoted to one very large project. Management wanted a somewhat wider distribution of effort. Without a much deeper investigation of the method, such a conflict might be attributed to either a faulty allocation algorithm or incomplete consideration of some factors in the problem.

The algorithm in the CAL method begins with a program that includes all the technical approaches to all the QMDOs. It then eliminates technical approaches, one at a time, according to the decrease in the "expected" value of the program per dollar cost that would result from removing the technical approach from the program. Those approaches that would result in the smallest loss of "expected" value per dollar cost are eliminated first. The elimination proceeds in order as long as a resource constraint or QMDO constraint is not violated. If elimination of a technical approach would violate one of these constraints, that technical approach is retained in the program, and the next in the order is tested. The procedure continues until the total cost of the remaining technical approaches falls within the limit of the total budget that is available.

The simplicity of such an elimination procedure is quite attractive. Unfortunately, it gives absolutely no assurance that the final program recommended satisfies the primary objective at least as well as other possible combinations of technical approaches. In other words, some of the eliminated approaches might be substituted into the program in a way that does not require more funds than the available budget and that results in greater expected value. The designers of the method admit that the algorithm may not generate optimum solutions (Ref. 16, p. B-8) but did not investigate the problem further because of the short term of their study contract. Such a shortcoming obviously places doubt on the advisability of applying the algorithm of the method.

The decision algorithm used in TORQUE funds each task in increments on the basis of the increase in utility per dollar increase in cost that results from funding the next increment of each task. The task increment with the highest ratio of added utility to added cost is funded first.

The TORQUE algorithm has shortcomings that arise both in the way that the various factors are combined in the utility function and in the particuler steps followed to determine the task increments that should be funded.

The most fundamental components of the utility function relate the development of a single technology objective to a single weapon system. These are shaped quite regularly, as is shown in Fig. 12(a). In this type of function, the funding and the timeliness function value, t_{jk}, vary within narrowly defined limits. The timeliness function is the principal determinant of the shape of u^F_{jk}. As the first year funding, F_{11}, is varied, the late and early points on the timeliness function (Fig. 2, above) generate the two corresponding corners of F_{11}. The segments of F_{11} to the left of late and to the right of early are the results of the timeliness function segments after the latest need date and before the earliest need date. The segment between the late and early points falls on a ray from the origin having a slope $W_i C_{i11} / \sum_y F_{y1}$, where W_i is the operational requirement weight assigned to the particular weapon, C_{i11} is the criticality of technology objective 1 to this weapon system, and $\sum_y F_{y1}$ is the total amount that still must be spent to achieve technology objective 1 in subsequent years, y.

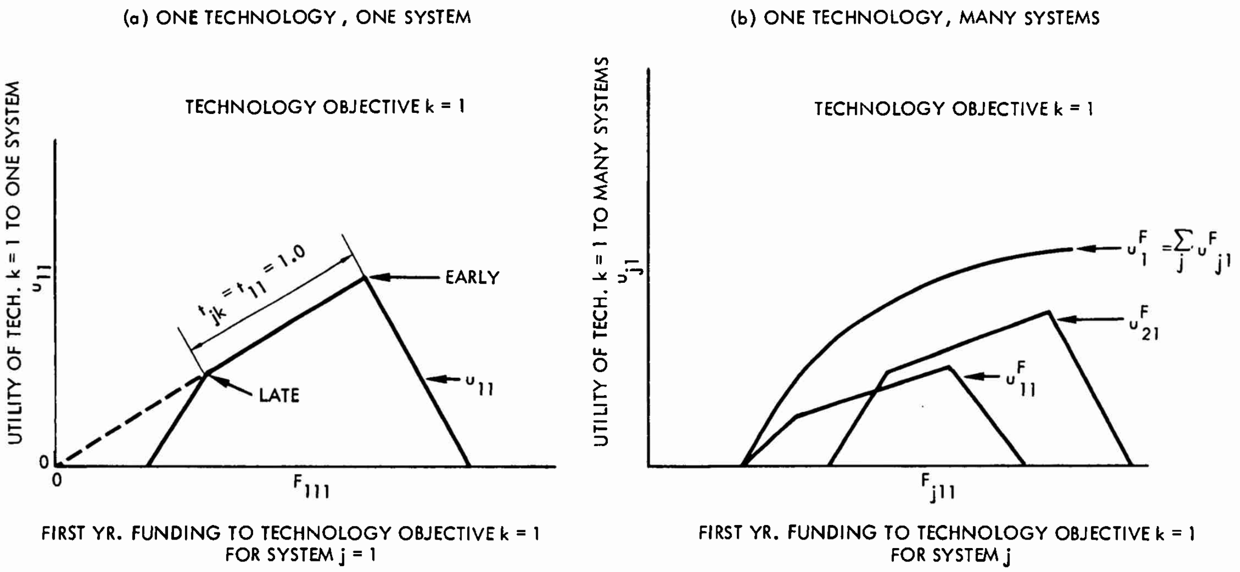

FIGURE 12. TORQUE Utility Functions

Questions about the appropriateness of the timeliness function were raised above in Section IV-C-7-b. Specifically, for present purposes, the segment for the period before the early date indicates that a technology objective developed more than two years before that date has absolutely no value. This implies that what might be learned in the development of this technology objective has absolutely no impact for what might be developed in other technology objectives related to the same system. It also implies that in the derivation of the u^F_{jl} functions for all weapon systems j, the planner knows with certainty that those systems exhaust the set of weapons to which the technology objective l will be applied.

The segment of the timeliness function for the period after the late date implies that completion dates can be known fairly precisely. However, one of the most important elements of risk in the development process is the time that will be required to bring an effort to successful completion. Time estimates in Exploratory Development are typically a few years; when combined with Advanced Development, these times may reach four to eight years. If the time estimates are in error by two years or more, the precision of the timeliness function downgrades the value of late developments inaccurately.

Figure 12(b) depicts the ideal aggregate utility function for a single technology objective, combining individual functions for a large number of weapon systems with overlapping need dates for this particular technology objective. However, the aggregation cannot ensure the regular shape shown in Fig.12(b). A single technology objective supporting two weapon systems that have somewhat separated initial operating capability dates could have a utility function shaped like the one in Fig. 13.

Inspection of the utility function (Section III-B-5) indicates quite clearly that the value of any technology objective can be increased simply by including in the analysis a larger number of weapon systems using it. That the weapon systems may or may not be effective in their missions, that all the weapon systems may apply only to a single operation or requirement, or that the weapon systems chosen in the program might fulfill the requirement several times over are not important to the utility function. In fact, it is quite unable to discern such irregularities.

These characteristics, in turn, indicate very strongly a basic, and serious, specification error in the utility function. It is an error that can possibly be corrected, but not by a few, simple modifications.

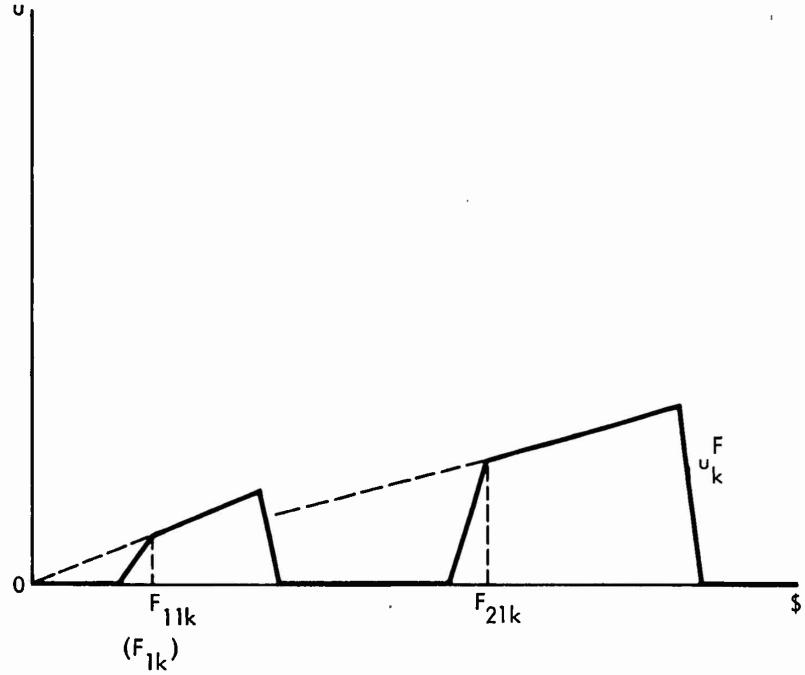

FIGURE 13. Utility Function of a Technology Objective Supporting Two Weapon Systems

The number of weapon systems actually considered in the formal allocation routine of TORQUE depends upon the discretion of the I.D. team. If it so desired, the team could introduce several variations on a particular weapon system, changing only one or a few component technology objectives, calling each a separate system, and thereby (consciously or not) biasing the allocation of resources towards those technology objectives held constant across the variations.

The strong independence or additivity requirement of the Churchman-Ackoff approximate measure of value also carries over into the algorithm. As a consequence of it, the value that will generally be attributed to the joint occurrence of two technology objectives used in separate but supporting weapon systems would be understated. This understatement will result if the analyst who devises the weights treats the weapons in their separate roles, as he should under the instructions for the consistent application of the value measure, and does not try to anticipate their supporting roles. Such an understatement will make these technology objectives less attractive for increments of funding than probably would be consistent with an efficient development program.

Sensitivity analyses, which show that small changes in the program solution result from rather wide variations in the weights, only beg this problem. As far as can be discerned, the sensitivity analyses retained the relative rankings that were given the separate operational requirements in the Churchman-Ackoff measurement procedure, whereas complementarity between weapon systems essentially breaks down the rankings.

In the computations followed to determine the task increments that should be funded, TORQUE does not use all of the points on the u_k function. Instead, it calculates selected points along that function for consideration in the computations. To do this, the procedure first determines the maximum first year funding, F_{1k}, that will be "allowed" for each technology objective. F_{1k} is the particular F_{ijk}, the first year fundings of the alternate budgets proposed by the Technology Team (cf. Fig. 10), that gives the maximum value $\frac{u_k^F}{F_{1jk}}$. In Fig. 13, the above procedure is equivalent to finding the value of u_k^F, corresponding to an F_{1jk}, that is connected to the origin by the ray of greatest slope. In this case the F_{1jk} satisfying this condition is F_{11k}. For the allocation iterations, the procedure then calculates and records the values of u_k^F at increments of $0.1nF_{1k}$, where $n = 1,2, \ldots, 10$.

As is evident from Fig. 13, the routine by which F_{1k} is chosen can exclude from the eligible options funding levels that could contribute substantial utilities to the exploratory development program. In that example, the higher funding levels, by which the technology objective is developed more quickly for use in high utility systems with sooner IOC dates, would be excluded from consideration once F_{1k} is set at F_{11k}.

The necessity of choosing a specific value, F_{1k}, is quite doubtful in the first place, but the particular procedure and criterion used lead to highly undesirable results.

The computation procedure is beset by another pitfall. As was indicated above, for the allocation iterations, the values of u_k^F are calculated and recorded only at the discrete intervals $0.1nF_{1k}$ for $n = 1, 2, \ldots, 10$. Once an initial level of funding is allocated to a technology objective, the addition to that level of a further increment of $0.1F_{1k}$ is evaluated on the basis of the utility that would be added per dollar of the funding increment. If the additional funds resulted in a funding level that corresponds to a "trough" in the u_k^F function, that is, an actual decline in the utility, that increment, and any further increments, in the funding of the technology objective would be ignored. In Fig. 14, the initial funding level of the technology objective is $0.1\bar{n}F_{1k}$, corresponding to "tangency" with $\bar{u}_k^{nF}$ (cf. the Appendix). If the funding increment, $0.1F_{1k}$, were to result in a funding level of $A(=0.1\bar{n}F_{1k} + 0.1F_{1k})$, the corresponding utility increment would be negative and additional funding rejected, despite the higher utilities possible at much higher funding levels.

3. Conclusions

This investigation has focused principally on the substantive issues involved in the formulation of a quantitative method for allocating the Exploratory Development budget. Therefore, it has placed somewhat less emphasis on the formal algorithms that are used to compute a recommended allocation. That emphasis does not mean, however, that the algorithm employed in a particular method is not important or that all algorithms are equally useful.

Obviously, the formulation of the planning model and the algorithm that will be employed in its computation are somewhat interdependent. However, the position of this investigation is that without an appropriate conceptual framework of the allocation problem, speculation about an algorithm remains largely a matter of mathematics.

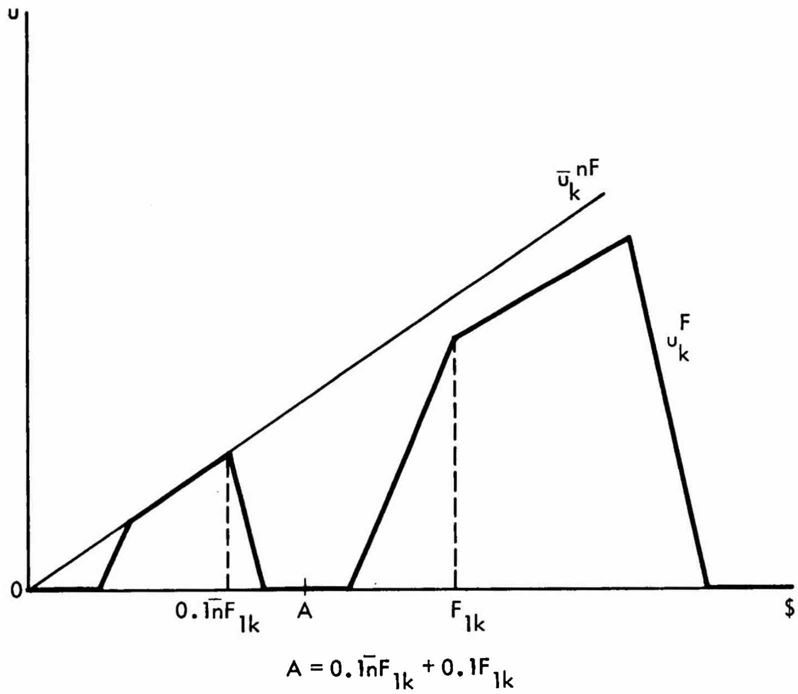

FIGURE 14. TORQUE Algorithm

Rather elaborate mathematical procedures are used in most of the methods that were reviewed. Some of these are new applications of existing optimization techniques, others are mathematical methods that give no assurance they converge to the best allocations, and still others are extensive computer search routines. Both the CAL method and TORQUE algorithms have shortcomings that cast serious doubt on their abilities to arrive at the best possible allocations.

Despite the increased availability of mathematical programming algorithms, devising an appropriate technique may remain a serious problem in the implementation of a quantitative allocation method. Consequently, a more thorough study of this feature of a quantitative allocation method should be made in conjunction with further in-depth study of the exploratory development planning problem.

F. FINDINGS ON EACH METHOD

This section contains comments on each method that do not fit into the general framework of analysis used above. Where appropriate, these are combined with the conclusions reached in the preceding analysis of the common features of the methods to support conclusions about the usefulness of each method.

1. Industrial Analog

The Industrial Analog is a highly simplistic method. Assuming that data are readily available for each of the variables, including commercial and Defense product complexities and lifetimes, and that relatively stable and precise functional relationships among these variables can be estimated statistically, little subsequent information and calculation would appear to be necessary to determine the allocation of 6.1 and 6.2 funds. It also requires little involvement by higher management in the distribution of funds among projects, tasks, or work units within the general technical fields.

Moreover, the Industrial Analog has obvious intuitive appeal. Because Defense Research and Exploratory Development problems are not tractable and generally cannot be evaluated easily, some kind of emulation of the apparent success by American industry would be highly attractive.

Several reasons were given above why this emulation and the data used to carry it out could be expected to lead to antiproductive results for military Research and Exploratory Development. However, one more aspect of the data deserves mention. The ratio of company-funded R&D expenditures to net sales used in the method is an industry-wide average, computed from individual company data that vary quite widely. Although they are averages themselves, the data in Table 7 give some indication of this variation by company size. Given this variability, a strong rationale would be needed to support use of the industry average in a scheme for determining DoD R&D funding. Because of the particular input requirements, progress in a technical field might well have been produced by companies spending more than the industry average. On the other hand, companies spending the average or more in another technical field may be using their R&D resources inefficiently so that similar "progress" could be achieved with lower expenditures.

The prescriptions of the Industrial Analog method could only contribute to the efficient achievement of national security goals by accident. Considering the nature of the method's objectives, the factors taken into account, and the relationships among the factors that make up its basic analytical framework, several severe and highly unlikely conditions must be satisfied before its allocations would even be fortuitously consistent with general Defense objectives. The same considerations suggest that, inasmuch as commercial objectives may be inappropriate and the ratios of company-funded R&D expenditures to industry sales are only remotely normative measures of behavior, Industrial Analog guidance may be absolutely wrong.

2. TORQUE Method

The procedures recommended in the TORQUE manuals and the composition of the Interdisciplinary Team impose on the overall planning process the condition that the relationships between weapon systems and technologies be considered systematically. This is very important for developing the priorities to direct the work that should be done in Exploratory Development to support future weapon systems.

Also the organizations and functions of the Interdisciplinary and Technology Teams require close coordination among the systems analysts and technologists. This interaction should promote a sharper awareness of each other's work on the part of both. The systems

TABLE 7. COMPANY FUNDS FOR R&D PERFORMANCE AS PERCENT OF NET SALES IN R&D-PERFORMING MANUFACTURING COMPANIES, BY INDUSTRY AND SIZE OF COMPANY, 1965

INDUSTRY	TOTAL	Companies with total employment of-		
		Less than 1,000	1,000 to 4,999	8,000 or more
Total....................	2.0	1.4	1.5	2.1
Food and kindred products.....	0.4	(a)	0.4	0.4
Textiles and apparel..........	0.4	(a)	0.5	0.5
Lumber, wood products, and furniture...................	0.5	(a)	0.5	0.3
Paper and allied products.....	0.7	(a)	0.9	0.6
Chemicals & allied products...	3.6	(a)	4.2	3.7
Industrial chemicals.....	3.9	(a)	4.1	4.0
Drugs & medicines........	5.6	3.1	6.7	5.6
Other chemicals	1.9	2.1	2.6	1.7
Petroleum refining & extraction	1.0	(a)	0.9	1.0
Rubber products................	1.7	1.1	1.0	1.9
Stone, clay, & glass products..	1.5	(a)	0.7	1.9
Primary metals.................	0.7	(a)	0.9	0.7
Primary ferrous products..	0.7	(a)	0.4	0.7
Nonferrous and other metal products..........	0.9	(a)	1.2	0.8
Fabricated metal products......	1.2	1.1	1.0	1.4
Machinery......................	3.2	1.6	1.6	4.2
Electrical equipment and communications...............	3.5	3.0	2.2	3.8
Communication equipment & electronic components...	4.2	4.7	1.0	4.5
Other electrical equipment	3.0	2.2	2.3	3.2
Motor vehicles and other transportation equipment.....	2.3	0.7	0.9	2.3
Aircraft and missiles..........	3.4	2.4	3.0	3.4
Professional and scientific instruments..................	4.2	2.9	3.4	4.9
Scientific & mechanical measuring instruments...	3.0	3.8	2.9	2.5
Optical, surgical, photographic, & other instruments.............	4.7	2.1	3.9	5.5
Other manufacturing industries.	0.7	(a)	0.8	0.4

(a) Not separately available but included in total.
Source: Ref. 20.

analysts should bring the current and projected states of technology more directly to bear upon the designs of prospective systems. The technologists should be able to appreciate better the functions that specific technologies can serve in weapon system development and direct their efforts accordingly.

While TORQUE has these commendable procedural features, it omits some other important considerations. It makes no provision for taking into account the non-Defense effort being expended upon the technologies that would support projected weapon systems. Systematic consideration of such work would prevent undesirable parallel efforts and waste. Also TORQUE makes no provision to prevent wide fluctuations in the funding (and consequently in the employment of specialized personnel and facilities) or particular technological areas from year to year. Large, rapid adjustments of this sort may be highly undesirable, particularly if maintaining some level of in-house capability were necessary to support minimum liaison with the scientific community, procurement specification operations, and contract monitoring.

Changes in the method are probably possible that would meet these objections. However, no simple modifications could be made that would remedy the shortcomings reviewed above regarding (a) the assignment of weights to the operational requirements, (b) the treatment of the technological composition of the weapon systems in a way that gives rise to both redundant and incomplete technological developments for supporting prospective weapons, (c) the ignoring of the risk of failure in each task, (d) the treatment of the timing of technological developments, and (e) the rules of choice used in the decision algorithm. All of these shortcomings are sufficiently fundamental that the analytical framework fails to address the budget allocation problem properly.

3. Naval Ordnance Laboratory Method

Striking parallels exist between the NOL method and TORQUE. The military worths of the EDGs in the NOL method are the same as the weights assigned to the operational requirements in TORQUE. The utility of a technology to an EDG in NOL is similar to the criticality of a technology to a weapon system in TORQUE. Also, both TORQUE and the NOL method omit any consideration of the risks of failure in any exploratory development task.

In addition, the NOL method does not lend itself to time-phasing the budgets that should be allocated to the various technologies. Nor does the way it takes into account the relationship of a technology to an EDG ensure that the expenditure derived by the algorithm for any technology will produce the level of the pacing parameter of that technology required in the EDG.

Finally, while the mathematics of the decision algorithm are sound when applied to the functions that are assumed in the NOL method to depict technological advance, evidence (such as that behind Fig. 9) indicates that the shape assumed for these functions may be inappropriate. If the shape assumed in the NOL method is inappropriate, the algorithm does not retain the property that it will generate the best possible allocation.

4. Air Force Flight Dynamics Laboratory Method

The FDL method also treats many of the factors it takes into account in ways that resemble the approach of TORQUE. Its primary objective and control variable are virtually the same; the procedure it uses to assign weights to operational requirements is also based on the Churchman-Ackoff approximate measure of value; its breakdown of systems into component technologies parallels TORQUE; it uses exactly the same weights to measure the criticality of a technical objective to a system; and it employs the same timeliness function to evaluate the time-phasing of the development tasks.

On the other hand, the FDL method tries to take into account variations in the performance of the different operational requirements by the different weapon systems. It tries to introduce some consideration of the risk that a particular technology objective may fit the design of projected systems. Also, the FDL method employs a long-standing, tried and proven decision algorithm: linear programming.

In sum, however, the FDL method does not address the problem of allocating the Exploratory Development budget more satisfactorily than TORQUE. The faults in their common features are so basic to an adequate formulation of the problem that the FDL method gives no more assurance a program it generates will be more consistent with or promote better national defense. Its treatment of risk is perfunctory, giving management little idea of how actual outcomes of development efforts could deviate from expected outcomes. Although it makes allowance for the performance of individual weapon systems in different operational requirements, it does not ensure any type of balance in the technical support given the range of the operational requirements. In other words, the resulting development effort could well be directed at fulfilling only one or a few operational requirements.

5. Cornell Aeronautical Laboratory Method

The CAL method is a departure from the general approaches taken in the TORQUE, NOL, and FDL methods. It links rather strongly the different technological efforts to the future weapon systems they support. The other methods impute value to the technological efforts on the basis of the weapons they support and subsequently drop that linkage. CAL's treatment of risk is noteworthy and probably merits further development. It takes into account the probability of success of each development task and compounds those for each system to derive the probability that the system will be successful. The method identifies the different resources used in the development tasks, maintains a record of those resource patterns, and ultimately ensures the use of more than some floor level or of less than some ceiling level of each resource if management wishes.

The CAL method does have faults, however, that are sufficient to prevent its acceptance as a satisfactory approach to the budget allocation problem. It does rely, in its current formulation, upon the assignment of values to the various QMDOs but gives no instructions on how this assignment should be made. Although this shortcoming might be overcome by judicious use of QMDO constraints, requiring the development of certain QMDOs, such a remedy must be worked out in some detail before it could be applied confidently. Beyond the valuation problem, technologies and tasks are treated too rigidly. In its present formulation, the CAL method treats technical approaches to a particular materiel concept as possible substitutes for each other. All materiel concepts to a QMDO are necessary to fulfill the QMDO. Much additional development of the method would be necessary to expand the formulation so that in its solution (a) trade-offs might be possible among technical approaches, (b) sequential and parallel development strategies could be derived, and (c) substitutions and synergisms among materiel concepts could be expressed and utilized.

Finally, another decision algorithm must be applied to its formulation of the factors that bear upon the allocation problem. The heuristic procedure recommended in its current stage of development could generate solutions that are inferior to other possible solutions. The steps in the algorithm do not guarantee that they are not ignoring combinations of tasks or QMDOs that would better serve the objectives and criteria of the method.

6. Hercules Method

The Hercules method was the only method among those reviewed that was not specifically formulated to deal with the problem of allocating the budget for Defense Exploratory Development. It was designed, however, to analyze the problem of allocating the budget for development work of a similar nature with commercial application. Being in a commercial setting, the formulators of the Hercules method could readily use measures of expected sales and profits as the ultimate measures of value for the development work involved. These are fairly easy to define, estimate, and verify among the management. Moreover, they can be transformed into an operational primary objective: the maximization of the profits that the development effort can ultimately generate for the company. The Department of Defense does not have similar measures of value readily available but more intensive study of the application of such a method could help to clarify how such a concept as cost savings might be used in a parallel fashion.

Other aspects of the Hercules method also probably warrant further study for possible applicability to allocating the Defense Exploratory Development budget. For example, the description of this method indicated that the formulators attempt to take into account both the trade-offs that might be made among technological components of prospective systems and the synergistic effects these components may have on one another. The timing of the development effort is investigated in terms of management's general time preferences rather than by some rigid functional rule. Also, the method introduces risk at several levels, such as prospective sales, margins, technical success, and timing.

Consideration of risk may be one of the weaker features of the Hercules method. Use of expected values or some particular level of probability to characterize the outcome of development events may hide very interesting and important information, e.g. the chances of incurring losses of unacceptable sizes. Management's overriding the allocation determined by the method to avoid concentrating the total development effort on one project may indicate that this weakness has been recognized.

7. Army Missile Plan

Along with the two following methods, the Army Missile Plan is a planning method that has a much more modest objective than the methods discussed above. Those methods attempt in some way to "optimize" the Defense Exploratory Development program. The Army Missile Plan attempts only to set out explicitly the technological development efforts that the laboratory personnel judge to be necessary to support the engineering and production of weapons proposed for future deployment. The efforts that are ultimately funded are those contributing in important ways to systems having the highest priorities.

Taking this restricted approach has two important results. First, it limits the number of options from which management can choose the development program to be implemented. This is obviously a shortcoming because, as is the case in almost any decision situation, the chance of increasing the contribution of the Exploratory Development program to national defense objectives should be higher if the decision maker can consider a broader set of options. This chance should be higher unless the options are expanded to the point that they are so numerous and irrelevant that they create confusion and some chance of choosing counterproductive programs.

Second, the limited approach avoids entanglement in a number of difficult problems. Complex value measures need not be devised, the trade-offs and synergisms among technologies are not considered, complicated but possible time-phasings of tasks are ignored, numerical descriptions of the risks involved are not needed, and intricately structured decision algorithms are superfluous. While all of these features are important aspects of any method for allocating the Exploratory Development budget, their exclusion may be less misleading than their being incorporated with highly inappropriate treatment.

Although the Army Missile Plan does not aim to devise the "optimum" Exploratory Development program, the information that it makes available to program management is an obvious benefit.

8. Air Force Directorate of Laboratories Plan

The DOL plan is even more modest than the Army Missile Plan. It has a similar objective but it does not resort to any scheme of priorities among the operational requirements or the systems that would be used in those requirements. Further, the DOL plan does not try to assign some measure of the contribution of any technology objective to the weapon systems. Technical planning objectives are set out apparently without analyses of possible trade-offs among the system components. The method does not even propose to rank the program elements or projects to set up some order of funding. Essentially, the DOL plan is a bare-boned trace of technological needs without any reference to the priorities of those needs or the risks that might characterize the tasks undertaken to fill them.

9. Army Research Plan

Like the Army Missile Plan, the Army Research Plan is only partly quantitative in its analysis of the allocation of the Exploratory Development budget. However, the two methods differ fairly widely in some important aspects. Both methods utilize a scheme of priorities to characterize the relative importance of individual operational requirements. They both also assign weights to the different technological efforts to indicate the contributions of the technological efforts to operational requirements or weapon systems.

The Army Missile Plan explicitly refers to specific weapons proposed for deployment to derive its pattern of technological effort while the Army Research Plan skips over systems and relates technologies directly to operational requirements. The Missile Plan attempts to trace specifically the funding of individual tasks whereas the Research Plan directs its attention to a somewhat broader question. It is concerned with the apparent general adequacy of funding for the broader technological effort encompassed by a program element which is an aggregate of tasks and projects. A third major difference between the Missile Plan and the Research Plan is their approach to the funding decision. The Missile Plan ranks the individual tasks for specific funding on the basis of their priorities and technical contributions, whereas the Research Plan has a number of staff-generated qualitative analyses that serve as the basis for recommendations on whether the program element should be given more emphasis. The staff does not rank in any order the program elements that are recommended for greater emphasis to suggest priorities even within that group.

The Research Plan is basically a method for structuring information and conveying it to management. The few aspects of the allocation problem that it does quantify are not used in computations to make precise recommendations on the distribution of funds. Consequently, the information is carried along quite visibly in the deliberations. Such a method can be an attractive approach to the allocation problem while more quantitative methods are being developed.

10. Another Service Method

This Other Service method is quantitative, having some features similar to those in the TORQUE, NOL, FDL, and CAL methods. Like TORQUE, NOL, and FDL, it uses a set of operational requirements in its derivation of the technological advances that the Exploratory Development effort should try to achieve. Like those same methods, it also requires that a measure of value be assigned the various operational requirements. The same problems that characterize the measures of value used in the more quantitative methods above apply equally to this method. The procedure for devising these weights assumes that the operational requirements are all independent of each other and that they are not fulfilled regardless of the amount of development work performed to support them.

Like the NOL method, this method does not make reference to prospective weapons to derive the Exploratory Development program. Technologies are applied directly to the operational requirements in the method without an evaluation of how the technologies make up specific weapons. Consequently, the technologies are considered as though they are quite independent of each other and are assigned weights that the analysts judge to reflect the isolated contribution of the technology to the operational requirement. As in the TORQUE, NOL, and FDL methods, such treatment leaves little room for considerations of how the technologies interact either as substitutes or as reinforcements for each other.

This method resembles the CAL method to some extent in the way that it treats the probabilities of the tasks achieving their technical objectives. The probabilities of success of all tasks directed at a specific technical objective are compounded to estimate the probability of at least one succeeding. However, unlike the procedure at CAL, these probabilities of success for the technical objectives are not used in any way to estimate the chances of progress in the different operational requirements.

This feature emphasizes the independence attributed to the various technical objectives. The technical objectives derive their values from the operational requirements they support, but no relationships among the technologies are necessary to fulfill that support.

The joint consequences of the independence and insatiability attributed to each operational requirement and the independence of the development tasks are that the Exploratory Development program may be directed at technologies that support the single operational requirement with the highest weight but that do not fit together in any feasible weapon design. In other words, without some specially designed constraints to prevent such an outcome, this method is quite open to generating a development program that is unbalanced and uncoordinated. For example, all Exploratory Development work might be directed toward the development of technologies that contribute only to strategic defense, but the results in propulsion, guidance, and warhead design would be incompatible in any specific weapon.

G. GENERAL DISCUSSION

This section summarizes the conclusions and recommendations that were reached in the above analysis, as they apply to the more quantitative methods, to the less quantitative methods, and generally to both groups of methods.

1. More Quantitative Methods

The more quantitative methods (Industrial Analog, TORQUE, Naval Ordnance Laboratory, Flight Dynamics Laboratory, Cornell Aeronautical Laboratory, Hercules, and Another Service) attempt to structure the allocation problem and express its factors almost exclusively in mathematical terms. They calculate a single, most desirable distribution of the development budget. All of these methods, except for Hercules, were devised to address the problem of allocating the budget of the Defense development program.

These methods are relatively complex; they treat factors in a precise fashion. They link the derivation of the development program to weapon systems that have been proposed for deployment against future operational requirements. Consequently, these methods provide a framework for systematic liaison among systems specialists, technologists, and research managers. This should help to broaden the development options that are considered in the derivation of the final program.

Complexity has the drawback, however, that the specific treatment given the various factors in a method may be obscure to everyone except the few specialists who formulate the method.

Despite their complexity and their attention to detail and precision, these methods generally treat too many of the important factors in the allocation problem inadequately or inaccurately. None of the formulators of the more quantitative methods meant for application to the allocation of Defense development resources appear to have been aware of the importance of delineating properly the scope and primary objective of their methods. They have all used a very broad-gauged objective for the allocation of the development resources (to devise the development program with the maximum military utility). Such an objective should open up the options that might be considered for the program. However, the linkages in the models among the development efforts, prospective weapon systems, operational requirements, and objectives are specified in ways that the choices made in the development program can also settle more comprehensive Defense program issues than should properly be determined by the development program. The choice is made among the alternative development efforts in such a way that it can also determine the emphasis that will be placed on the development of specific weapon systems and consequently on the fulfillment of the various operational requirements. This order of determination is the reverse of good decentralized programming.

None of these methods use constraints on the set of development options that is considered in the allocation problem in such a way that prevents this reversal.

Most of these methods treat individual development efforts as though they are independent of each other, particularly in the sense that they are not interrelated as components of proposed weapons. A similar independence is attributed to other factors as well. Weapon systems are treated as though they have little interaction with each other and operational requirements are treated as though they are fulfilled in isolation from each other.

Independence among the development efforts, weapons, and operational requirements is necessary to the procedure that is used to impute value to these factors. To the extent that the independence is not real, the values imputed to the factors are inaccurate and misleading.

None of the more quantitative methods specify with precision the development costs that should be analyzed in the allocation problem. They are particularly remiss in setting the ground rules for what development resources should be taken into account and for the treatment of expenditures that must be made in the future. How should real estate that is Government-owned and used in a development effort be treated? Should the costs of military manpower employed in development be treated as a development cost? How should appropriations needed in future budget years be treated?

None of the more quantitative methods address the important managerial problem of how the actual technical, cost, and timing outcomes of the development effort may jointly deviate from the technical, cost, and timing estimates made at the time the allocation is decided. They all employ point estimates of these factors without providing for the collection of data on them as efforts progress or for the updating of the estimates in subsequent allocations.

The more quantitative methods for allocating resources within Defense Exploratory Development are at a rudimentary stage in their own development. Each of the methods reviewed has identified the important considerations in the allocation problem. However, as was pointed out immediately above, the particular manner in which individual factors have been expressed mathematically and incorporated into the specific analytical frameworks is only a first, and often inaccurate, effort.

Consequently, none of the more quantitative methods reviewed should be applied, in their present formulations, to allocating resources within Defense Exploratory Development.

The inapplicability of these particular methods, however, should not discourage further study and development of such methods. Properly formulated methods could provide valuable assistance to management for its determination of the development program.

Further study should be made of methods that have been devised for application to resource allocation within industrial research. Of the more quantitative methods, the Hercules method structured the problem and treated the important factors most appropriately.

Specifying an appropriate primary objective is a particularly difficult obstacle to the formulation of a method for allocating resources within Defense Exploratory Development. The Defense problem has no readily adaptable counterpart to the profit-maximization objective used in the Hercules method. However, other industrial methods could be studied for techniques that may be used to express objectives applied to the limited scope of a company's development program. In large companies these objectives may be derived and decentralized from that of the overall company objectives in a way that resembles the subordinate role of Defense Exploratory Development.

Further study should also be made of the adaptation of a cost-minimization objective to the allocation of resources within Defense Exploratory Development. This investigation should begin with the studies of cost savings imputed to the C-141 transport and the AN/SPS-48 radar that were reported in HINDSIGHT (Ref. 4). The objective assigned to Exploratory Development would be to generate the technological progress supporting the development of weapon systems that would produce the greatest cost savings while fulfilling a given set of missions.

2. Less Quantitative Methods

The less quantitative methods (Army Missile Plan, Air Force Directorate of Laboratories Plan, and Army Research Plan) do not try to express mathematically some important factors in the allocation problem. They place much greater reliance upon managerial judgment to take into account such factors. These methods may recommend an allocation of resources among proposed development efforts but without the numerical precision of the more quantitative methods and without contending that the recommendation is the single, most desirable allocation.

The less quantitative methods attempt primarily (1) to record explicitly information on some relevant considerations that must be made in determining the allocation of the development budget and (2) to transmit this information visibly to all the levels of management involved in determining that allocation.

These methods have more narrowly circumscribed objectives than the more quantitative methods. They focus tightly on deriving those technical advances that would support a very limited and specific set of future weapon systems. As a result, the allocations chosen using one of these methods should be internally consistent and provide an integrated set of technologies in support of some set of weapon systems proposed for future deployment.

On the other hand, being tightly focused, the less quantitative methods are not likely to take into consideration a set of possible and useful development efforts that is as extensive as the set made visible in the more quantitative methods.

These methods leave to management's judgment the consideration of some factors that are recognized to be important but for which no precise numerical expression is devised. Management must elect whether and how to take into account such factors as the contribution of a particular weapon system to an operational requirement, the importance of a technical advance to a weapon, the relevance of various kinds of costs, and the possibility that actual cost, timing, and technical results may deviate from those predicted at the time the allocation decision is made. Undoubtedly, these factors contain very substantial subjective components. However, if the consideration they receive is not carefully specified and they are not made entirely explicit, much of the decision process for allocating the development resources is left obscure. As a result, the rationale for the chosen allocation remains largely implicit and difficult to review with the ultimate consequence of appearing arbitrary.

Because of the limited extent of the set of options they take into consideration and the lack of precision in their treatment of some important factors in the allocation problem, these methods may not choose the development programs best supporting higher order Defense goals.

Less quantitative methods such as those reviewed in this study are fairly well developed. More or less formally, this type of analysis of the allocation problem has provided the background for actual resource distribution. Consequently, it has benefitted from the experience of its practitioners and the informal feedback that the latter have received in the budgetary process.

Undoubtedly, many research managers should find some one of these methods a convenient framework for organizing the information that they want readily available when they must decide their allocation of development resources.

Further development of the less quantitative methods would probably give them a greater resemblance to the more quantitative methods. The less quantitative methods must describe more explicitly and precisely such important factors in the allocation problem as the technical, cost, and timing risks involved in the development of technology. Specific expressions, possibly numeric, for these factors and the relationships of technologies to weapon system characteristics would permit the decision maker to consider them more systematically in choosing his allocation of resources.

3. More Quantitative and Less Quantitative Methods

All of the methods that were reviewed approach the development programming problem in a prospective sense only. That is, they are concerned with planning, before the fact, the distribution of development resources that should be made in the future to proposed development efforts.

However, by itself, prospective planning may not very effectively influence the course of actual development effort. Planning must be integrated with techniques for controlling actual resource use. One of the principal aids to control is a record of resource consumption and outcomes that follows the same framework and terms used for the prospective plans. None of the reviewed methods provide for a systematic recording of the actual cost, time, and technical outcomes of the funded development efforts in a format that would facilitate comparison with the estimates underlying the planned allocation of resources. This could be an invaluable source of information for subsequent applications of one of the methods and for making adjustments to the allocations that were made in the past to current development efforts.

A similar kind of default on the part of the methods' formulators is the basis for the concern expressed above about the objectivity or reliability of the measures of value (Section IV-C-1-b) and the measures of the relationships of technologies to weapon systems (Section IV-C-4-b) that are used in the methods. For factors such as these, the formulators have not established measurement procedures that can be used with confidence that a given set of observers making the measurements would arrive at the same quantities for the same factors under fixed conditions but at different times. Nor do the procedures provide for measuring the variation that might arise in the measurement of these factors by different sets of observers.

Similarly, but on a larger scale, the formulators have not proposed that the methods be subject to a serious test of their overall reliability. Such a test would involve measuring the extent to which a given set of decision makers might arrive at different resource allocations (1) applying at different times a given method to the same external threat, development opportunities, and other conditions, or (2) applying different methods to a fixed context at the same time. Other measures of reliability could be made from having different sets of decision makers apply a given method, then different methods, to a fixed set of conditions.

One further problem with the methods arises out of these measurement difficulties. Because the reliability of the measures of some important factors is not demonstrated and because the objectives adopted in some of the more quantitative methods are quite hazy, there is no way to verify retrospectively whether the chosen program actually achieved its objective. How can the utility of the technological advances achieved by a program be measured in a way that can be compared with the utilities estimated at the time the allocation is made?

The same type of difficulty extends to measuring the relative benefits of using one method as opposed to any other. The formulators of the methods have not indicated how a test might be devised to demonstrate that the program resulting from the allocation reached by a particular method is in any way superior to the program generated by another method, or without any method.

APPENDIX

TORQUE BUDGET ALLOCATION ALGORITHM

The TORQUE budget allocation algorithm consists of two major operations, each of which is further divided into a set of procedural steps. The first major operation is the explicit expression of each technology objective "utility function." The second major operation uses these "utility functions" in an iterative procedure for distributing the available funds among the technology objectives.

Technology Objective Utility Functions

The first major operation of the allocation algorithm is the explicit generation of the utility function for each technology objective through the following steps.

For each technology objective

(1) Calculate the values of u_k^F, using in the technology objective "utility function" the first year fundings, F_{1jk}, from the alternate budgets proposed by the Technology Team to support the different weapon systems,

(2) Find $\underset{j}{\mathrm{Max}}\left[\frac{u_k^F}{F_{ijk}}\right]$ among those u_k^F calculated in (1) and designate the corresponding F_{1jk} as F_{1k},

(3) Calculate the values of u_k^F at discrete funding levels, using in the technology objective utility function increments of one-tenth the value of F_{1k}, or $0.1F_{1k}$,

$0.1nF_{1k}$ = cumulation of n increments of F_{1k}, where n = 1,2, ...,10,

u_k^{nF} = value of the technology objective utility function at $0.1nF_{1k}$,

(4) Record the values of u_k^F calculated in (3) as the technology objective utility function.

Budget Allocation Iterations

The iterative procedure for distributing the program budget is carried out in the following steps.

(1) From the utility function of each technology objective recorded in the last step above, calculate

$\frac{u_k^{nF}}{0.1nF_{1k}}$, for each n, find $\underset{n}{\text{Max}}\left[\frac{u_k^{nF}}{0.1nF_{1k}}\right]$ and set it equal to $\bar{u}_k^{nF}$,

(2) Find $\underset{k}{\text{Max}}\left[\bar{u}_k^{nF}\right]$ and fund the technology objective, k, for which $\bar{u}_k^{nF}$ is the maximum at $0.1nF_{1k}$, set $0.1nF_{1k} = \Delta B_1$,

(3) Calculate $B_1 - \Delta B_1 = B_2$, where B_1 = the total budget available for the program,

(4) Calculate $\frac{u_{k'}^{(n+1)F} - u_{k'}^{nF}}{0.1F_{1k'}} = \frac{\Delta u_{k'}^{nF}}{0.1F_{1k'}}$ for each technology objective k' already funded to $0.1nF_{1k}$,

(5) Find $\underset{k,k'}{\text{Max}}\left[\bar{u}_k^{nF}, \frac{\Delta u_{k'}^{nF}}{0.1F_{1k'}}\right]$, where k indicates those technology objectives not yet funded, add to the funding of the technology objective that satisfies the maximum the amount $0.1F_{1k'}$ or $0.1nF_{1k}$ as appropriate, set the latter amount equal to ΔB_2,

(6) Calculate $B_2 - \Delta B_2 = B_3$ and, in general, $B_I - \Delta B_I = B_{I+1}$, where I is the number of allocation iterations,

(7) Repeat steps (4), (5), and (6) until one of the following conditions holds

(a) $B_{I+1} = 0$,

(b) each remaining possible increment of funding, $0.1nF_{1k}$ for those technology objectives not yet funded or $0.1F_{1k'}$ for those technology objectives funded to some extent (but not to $F_{1k'}$), is greater than B_{I+1},

(c) all technology objectives k are funded to their respective F_{1k}, or

(d) all technology objectives are funded to some extent, and all $\dfrac{\Delta u_{k'}^{nF}}{0.1F_{1k'}} \leq 0$.

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